



# Comparison of posterior indirect adhesive restorations (PIAR) with different preparation designs according to the adhesthetics classification. Part 1: Effects on the fracture resistance

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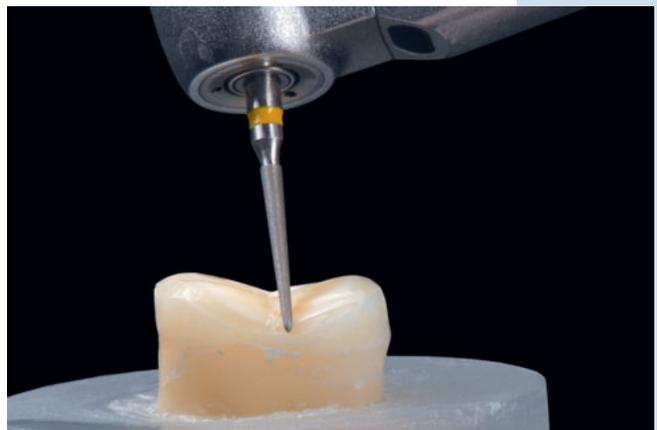
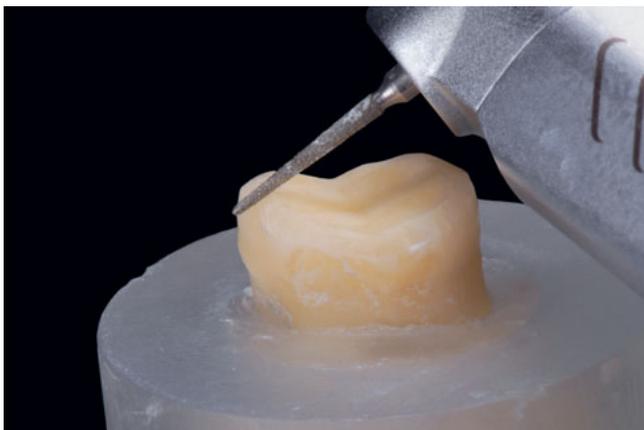
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## Abstract

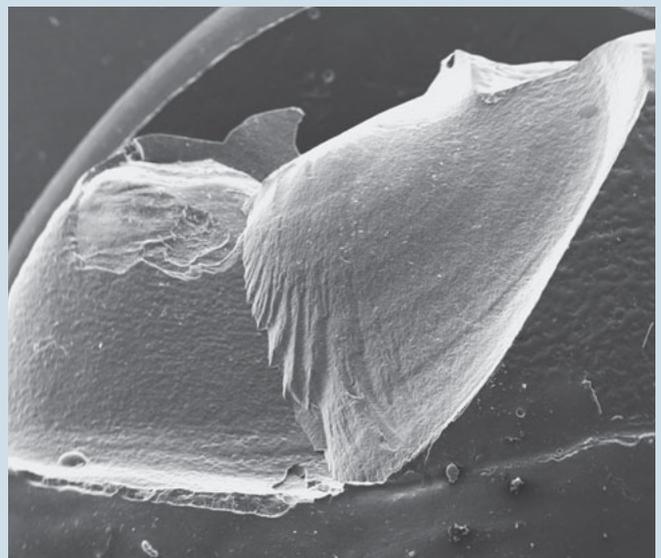
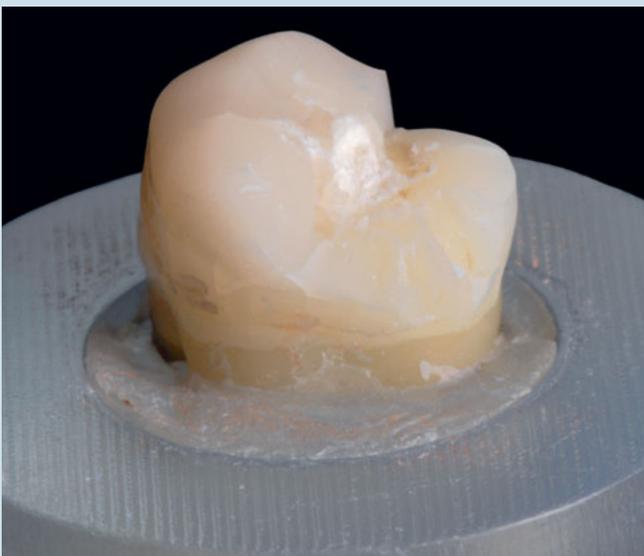
**Aim:** To investigate whether: 1) in the adhesive era, a full-crown restoration in a molar tooth is more resistant compared with an overlay-type restoration; b) a posterior indirect adhesive restoration (PIAR) is similar to a sound tooth from a mechanical point of view.

**Materials and methods:** Seventy extracted molars were divided into five groups (1. Butt Joint; 2. Full Bevel; 3. Shoulder; 4. Full Crown; 5. Sound Tooth (control); N = 14) and prepared with four different PIAR overlay design types (according to an adhesthetics classification). Seven expert dentists performed all the preparation and cementation phases with codified protocols. A CAD/CAM workflow was used to realize the 56 monolithic lithium disilicate restorations. The samples were tested with thermomechanical aging

(margin quality data will be given in Part 2 of this article series), and the resistance to fracture was then tested and analyzed.

**Results and conclusions:** In terms of fracture resistance in a situation of overload and within the limitations of the present study, it is possible to conclude that the Full Bevel group showed higher fracture strength than all the other groups. All PIAR restorations performed equally or better than the natural control tooth in the Sound Tooth group. The Full Crown group did not perform better than partial overlay PIAR. The fracture types were limited to the crown in 50% or more of the samples; the rest involved the cervical part of the root. The preparation design that involved the root the least was the Full Crown group (14%).

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## Introduction

In the present adhesive dentistry era, the following questions arise when considering restorations with metal-free materials: Can a full crown in a posterior tooth guarantee a better prognosis than a partial restoration? Is paying a higher biologic price in terms of tooth preparation the best way to prevent fractures? These questions informed the present study, which attempted to investigate the resistance of different overlay partial restorations compared with a natural tooth and full-coverage crowns.

Full-coverage crowns constitute the most common fixed prosthodontic treatment.<sup>1</sup> According to a survey conducted by the American Dental Association, more than 45 million dental crowns (37 million of which were porcelain-based) were placed in private dental offices in the USA in 1999.<sup>2</sup> After 20 years, the question is whether it is better to place a full-crown or partial restoration as an overlay. This is a very important question in the adhesive era because, if we can achieve better or equivalent performances for partial indirect adhesive restorations (PIAR) in terms of fracture resistance, dentists would generally prefer the more conservative approach in order to guarantee more favorable reintervention due to the preservation of hard tissue. Using an adhesive technique is mandatory with new materials and with adhesive preparation designs (without important friction and retention).

Various articles in the literature compare partial and full-coverage crown designs.<sup>3</sup> A study by Guess et al<sup>4</sup> investigated the influence of the thickness and the extension of different premolar partial crowns made of a pressed lithium disilicate ceramic. No significant effect on the fracture resistance of pressable lithium disilicate ceramic onlay restorations was found in this study when the preparation depth was reduced to 1.0

and 0.5 mm. However, lower failure loads for palatal onlays and complete veneers were found when the preparation depth was reduced to 0.5 mm. Quantitative analyses of various preparation designs have shown that the amount of tooth structure removal from onlay and partial crown preparation configurations in posterior teeth can be reduced by more than 40% compared with complete coverage crown preparations.<sup>5</sup> Gold is mentioned as the most established material for partial restorations. The clinical long-term success rate of cast partial restorations made from high gold alloys is between 60% and 96% after 10 years. The long-term success of gold is primarily limited by biologic factors such as secondary caries, endodontic complications, and tooth fractures. Technical failure is predominantly caused by loss of retention, extensive wear, and inaccurate margins.<sup>6</sup> With the development and improvement of reliable adhesive bonding techniques, minimally invasive dentistry has become a field of great interest in modern restorative dentistry. Preserving tooth structure is critical for the longevity of teeth and restorations.<sup>6</sup>

As a result of the above, various treatment concepts such as defect-oriented veneer restorations have evolved for the anterior dentition.<sup>7</sup> However, for compromised teeth in the posterior dentition, minimally invasive dentistry is most often associated with direct composite resin restorations.<sup>8</sup> Nowadays, it is quite common for dentists to perform PIAR, and while the preparation design probably influences clinical performance, there is insufficient scientific data in the literature for dentists to make decisions regarding types of restorations.

Minimal ceramic thicknesses ranging from 1.5 to 2 mm are recommended by most manufacturers. However, these thickness requirements are mostly based on results of laboratory tests with limited clinical evidence.<sup>9,10</sup> Different materials can be

used to finalize a PIAR restoration such as resin-based composite materials or glass-ceramics, especially the highest strength ones, and all of them can be used with a layered or monolithic approach. Especially when a monolithic approach is used, modern materials such as lithium disilicate can guarantee a good performance of prosthetic crowns even with smaller wall thicknesses, achieving a thickness of 1.0 to 1.5 mm.<sup>11</sup> It is recommended to increase ceramic thicknesses with corresponding tooth structure removal to prevent failure through restoration fracture. However, when an extensive amount of tooth structure has been destroyed by caries, attrition, or erosion, preservation of the remaining hard tissue is crucial.<sup>12</sup>

The use of new-generation all-ceramic restorations and adhesive systems can lead to improved preservation of the residual tooth structures, especially for the treatment of a single tooth.<sup>13</sup> Lithium disilicate glass-ceramic, a ceramic material that was introduced to the dental market in 2005, is composed of quartz, lithium dioxide, phosphorus oxide, aluminum, potassium oxide, and other components. It is characterized by a flexural strength of up to 440 MPa.<sup>14</sup> The mechanical stability of this type of ceramic is assured by the embedment of lithium disilicate crystals ( $\text{SiO}_2$  to  $\text{Li}_2\text{O}$ ) into a matrix of glass that minimizes microcrack propagation.

The adhesive technique used plays an important role in this regard, since adhesively bonded all-ceramic restorations show a higher fracture resistance than conventionally cemented restorations.<sup>15</sup> Depending on the adhesive system used, adhesive restorations bonded with total-etch techniques can reach a bond strength of up to 28 MPa within enamel and 13 to 20 MPa within dentin.<sup>16</sup> Immediate sealing of the freshly cut dentin has been suggested to improve bond strength.<sup>17</sup>

A further factor influencing the fracture resistance of all-ceramic restorations is preparation design. For these restorations, the preparation should be carefully rounded and be free of any internal sharp angles.<sup>9</sup> The thickness of the ceramic restoration is another factor influencing its fracture resistance.<sup>18</sup> Scientific evidence on the ideal minimum thicknesses for lithium disilicate ceramic partial restorations or occlusal veneers is still scarce. Bonded occlusal veneers made of IPS e.max CAD (Ivoclar Vivadent) were found to resist forces of up to 800 and 1000 N when their thickness was 0.6 to 1.0 mm or 1.2 to 1.8 mm,<sup>19,20</sup> respectively; these values are only slightly inferior to those of monolithic full crowns of comparable thickness.<sup>21</sup>

The rehabilitation of patients with increased chewing forces due to bruxism or other parafunctions represents a particular challenge in restorative dentistry.<sup>3</sup> In most studies on all-ceramic restorations, patients with parafunctions were excluded due to the increased risk of fracture. Restorations with metal occlusal surfaces were the standard of care for these patients; however, such restorations did not meet the patients' esthetic demands.<sup>22</sup> Minimally invasive design approaches have been advocated for teeth where a significant amount of dental tissue has already been lost by wear and erosion because further tooth preparation may be counterproductive in these cases.

The aim of this article is to outline some important aspects of clinical protocols related to the fracture resistance of PIAR. The term 'adhesthetics' is a coinage, combining the terms adhesion and esthetics. This adhesthetics approach and its protocols give a concrete solution for some practical aspects of adhesive dentistry.

The purpose of this study (codified as ARG2), performed by the Adhesthetics Research Group in collaboration with the University of Trieste, Italy, was to evaluate the



Fig 1 Prepared samples and bur kit before the PIAR preparation phases.

fracture resistance and failure modes of full-coverage molar restorations in lithium disilicate with an occlusal thickness of 1 mm, with different preparation designs, comparing full-crown restorations with three different overlay-type restorations (butt joint, full bevel, and shoulder) and a natural tooth without restoration after simulated thermomechanical loading (TML), according to the adhesthetics PIAR designs.<sup>23,24</sup> Apart from the preparation designs, all other variables were eliminated for the purposes of this study; thus, the same restorative material (lithium disilicate), technique, cementation material, and dentin conditioning were used. The null hypothesis was that no significant difference would be found with respect to fatigue resistance among the PIAR groups, complete molar crown, and natural molar tooth.

## Materials and methods

### Specimen preparation

Seventy human third molars, extracted for periodontal reasons, without any caries or

fillings, were cleaned and stored in a 0.1% thymol solution. Study participants provided informed consent under protocol 194/2019, approved by the Regional Ethical Committee (CEUR) of Friuli Venezia Giulia, Italy. Following extraction, plaque, calculus, and periodontal fibers were removed, and each tooth was stored in 0.5% chloramine at 4°C for up to 30 days.

The roots of the teeth were mounted in resin cylinders (diameter of 20 mm up to the cervical third of the root; 2 to 3 mm apart from the cemento-enamel junction [CEJ]) and fixed with transparent acrylic resin (Ortho-Jet; Lang Dental; Fig 1).

### Tooth preparation

The teeth without endodontic treatments were randomly assigned to five test groups with 14 teeth in each group. Depending on the preparation technique to be used, the teeth in each group were subdivided into four groups to receive full-coverage monolithic lithium disilicate restorations (IPS e.max LT A2 CAD; Ivoclar Vivadent). Seven experienced operators in four different dental clinics in Italy (Federico Ferraris, Sergio Cincera, and Michele Tognini in Alessandria; Eliseo Sammarco in Manduria; Gabriella Romano in Casarano; and Tommaso Mascetti and Marco Testori in Milan) performed all the operative phases for the sample preparation, dentin sealing, and cementation.

The teeth were prepared using a red ring high-speed handpiece (Lux M25 L; KaVo) and burs from the Adhesthetics Indirect Kit (LD 1372; Komet) designed by Federico Ferraris, as described in the following sections.

#### Group 1: Butt Joint

The following designs describe a didactical preparation as it would occur in a clinical environment. This type of design is used when, for example, there is a central build-up on a mesial, occlusal or distal (MOD)

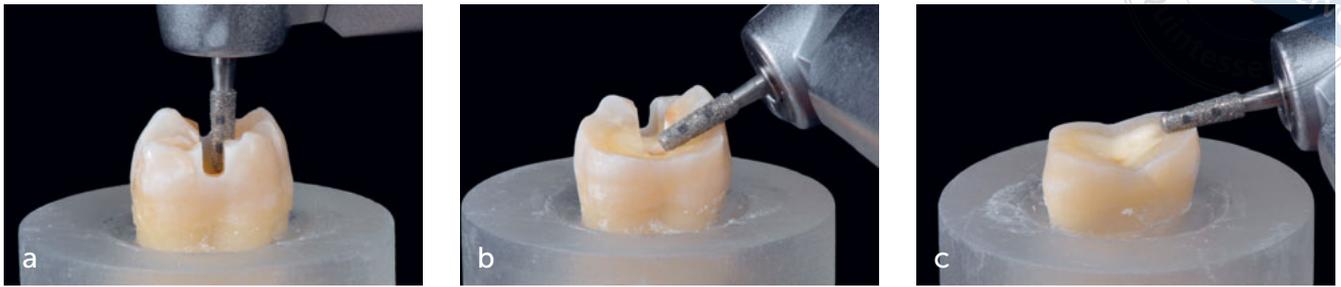


Fig 2a to c Butt Joint preparation phase: occlusal reduction.



Fig 3a to c Butt Joint preparation phase: proximal slot and finishing steps.

cavity. Basically, it is the type of restoration performed on a nonvital tooth where the mesial and distal slots are caused by previous caries.

Occlusal vertical grooves with a depth of 2 mm (even though the restoration was planned as monolithic lithium disilicate with an occlusal thickness of 1 mm) were made with a medium-grit 107  $\mu\text{m}$  tapered bur (959KR 314 01; Komet) with laser depth marks. The grooves were drawn from the center to the outer perimeter of the teeth following the progression of the occlusal plane until the external surface of the tooth (Fig 2). A reduction connecting the occlusal grooves was carried out with a coarse-grit 151  $\mu\text{m}$  tapered bur (6847 KRD 314 016; Komet) up to a bit over the second depth mark, with the idea of having a slot of about 3-mm deep x 1-mm thick and 4-mm wide in a buccopalatal direction. Therefore, the

total reduction in the interproximal boxes was 5 mm, so in this area the finish line was close to the level of the CEJ, knowing that the restoration would have close to a minimal thickness of enamel.

The intention of the main design was to make the preparation more horizontal in the external part of the buccal and palatal margins, maintaining the oblique occlusal plane and converging toward the center of the tooth. The inside corners were rounded, and the edges of the boxes were smoothed, first using a fine-grit 46  $\mu\text{m}$  tapered bur (8847KR 314 016; Komet), and then a bur with the same shape and diameter, being an extra-fine-grit 25  $\mu\text{m}$  tapered bur (959KREF 314 018; Komet). Following this, the final occlusal and marginal finishing was performed (Fig 3). On the main surfaces, a rubber polisher was used for the final polishing (9608 314 030; Komet; Fig 4).

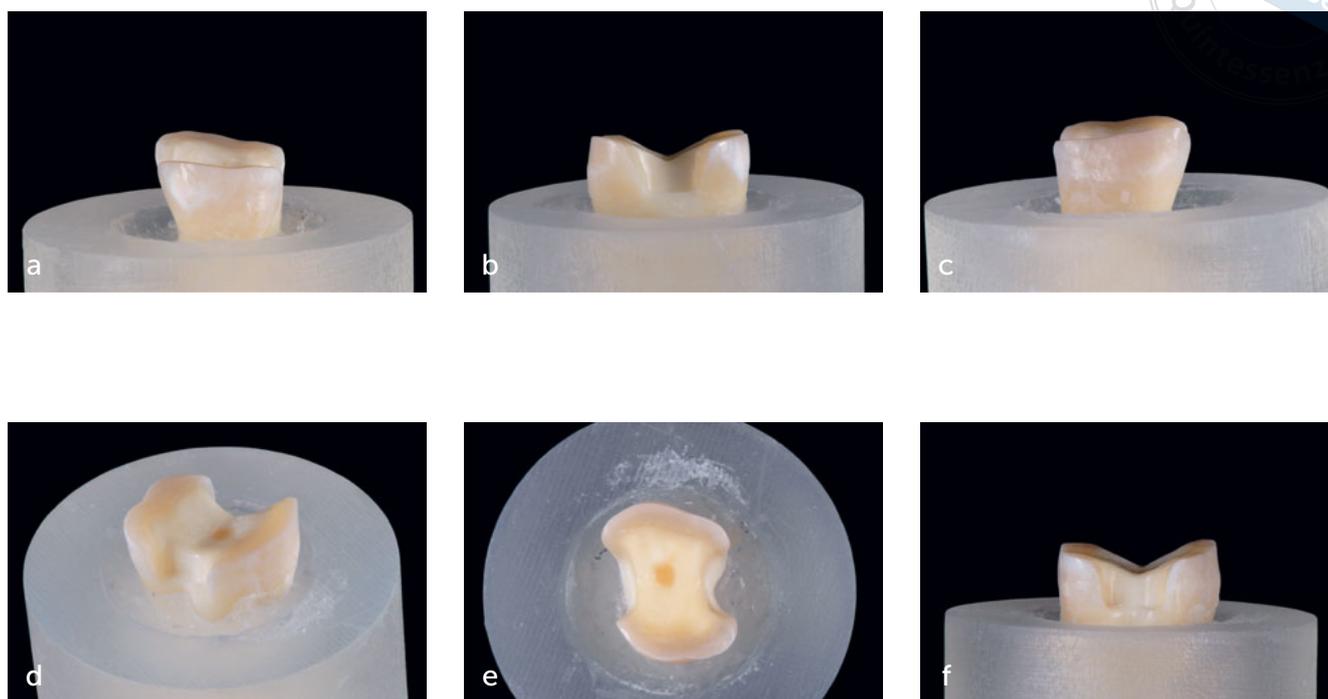


Fig 4a to f Butt Joint preparation finalized.

#### Group 2: Full Bevel

The advantages of this preparation are that it is very minimal and is suitable for creating tabletop coverings to increase the surface of support on the enamel. In this case, the occlusal reduction was performed as for the previous design (Butt Joint) using the same burs. As the preparation would not have reached the CEJ in the proximal areas, a circumferential bevel was performed, also in the interproximal part. Monolithic lithium disilicate was planned as the final restoration, with an occlusal thickness of 1 mm, as for the other preparation designs. The occlusal reduction of 2 mm was performed with a medium-grit 107  $\mu\text{m}$  tapered bur (959KREF 314 018), creating the horizontal grooves both in the central part of the tooth and toward the ridges. Following this, the grooves were connected using the same bur, retaining the inclined plane with respect to the anatomical

cusps. Instead of regularizing toward the external walls (as would be done to create a butt joint), a bevel was made with a medium-grit 107  $\mu\text{m}$  pointed bur (858 314 010; Komet), oriented at 45 degrees, thus obtaining a 1-mm bevel. A slightly deeper bevel (about 2 mm) was achieved on the interproximal surfaces by slightly tilting the bur about 25 degrees, with the intention of simulating an inclusion of the contact area, as for the other preparation designs (Fig 5). The major difference with this type of preparation was that the margins were all maintained in the enamel. All the internal corners were rounded. Then, the extra-fine-grit 25  $\mu\text{m}$  finishing burs with the same shape and dimensions as the previous ones (959KREF 314 018 and 858EF 314 010; Komet) were used for further finishing of the preparations (Fig 6). On the main surfaces, a rubber polisher was used for the final polishing (9608 314 030; Fig 7).

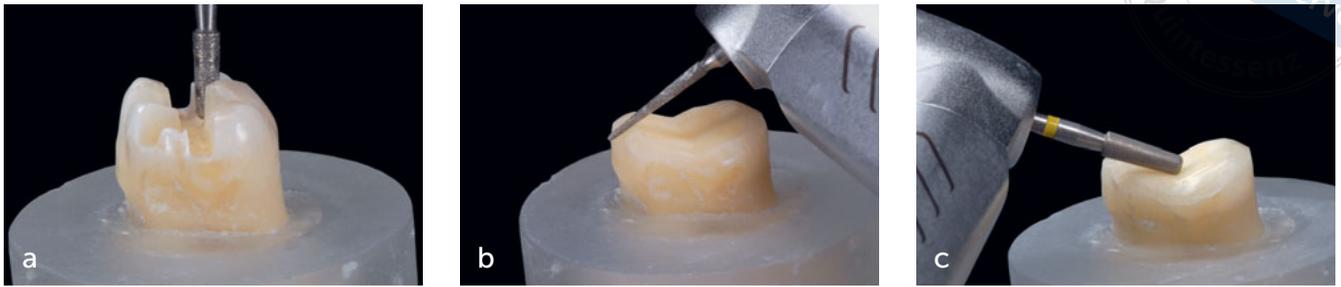


Fig 5a to c Full Bevel (360-degree) preparation phase: occlusal reduction and bevel creation.

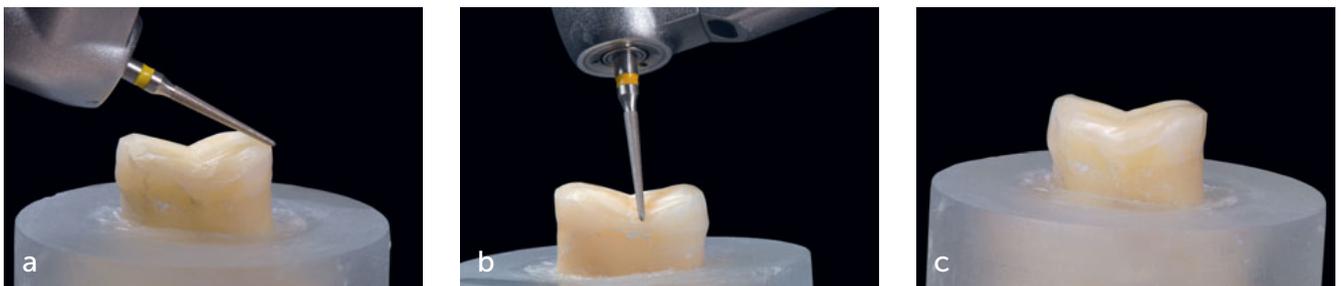


Fig 6a to c Full Bevel preparation phase: finishing steps.



Fig 7a to c Full Bevel preparation finalized.

*Group 3: Shoulder*

This preparation is not generally performed on all the tooth perimeters (360 degrees) in the clinical situation; however, for the purposes of comparing it with the other preparation designs, it was decided to perform one type of shoulder preparation on all the tooth perimeters. In the adhesthetics protocols, the shoulder for partial PIAR is indicated when there is a cusp fracture at the 1/3 mid-cervical level.

The shoulder was reduced 2 mm (even though the restoration was planned as monolithic lithium disilicate with an occlusal thickness of 1 mm), as for all the preparations, and was then covered by a 1-mm restoration. The guide grooves were performed with depth mark burs following the occlusal line of the tooth. The occlusal reduction connecting the 2-mm grooves was performed with the same bur (959 KRD 314 018; Komet). Unlike the other preparations,

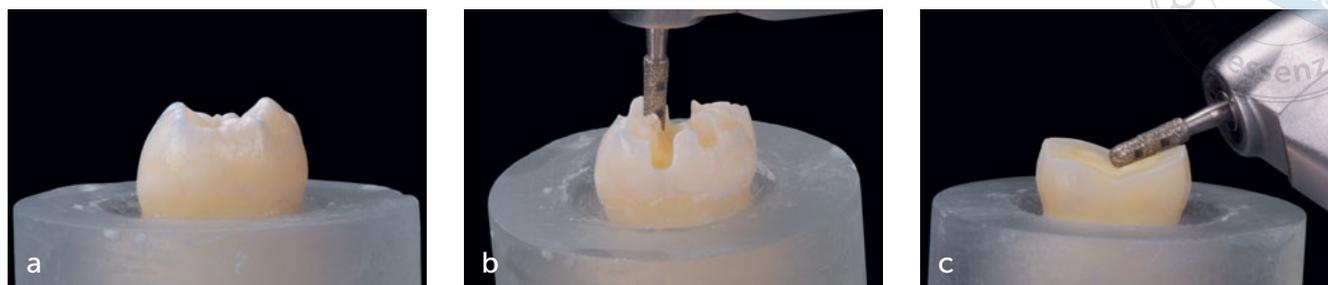


Fig 8a to c Shoulder (360-degree) preparation phase: occlusal reduction.

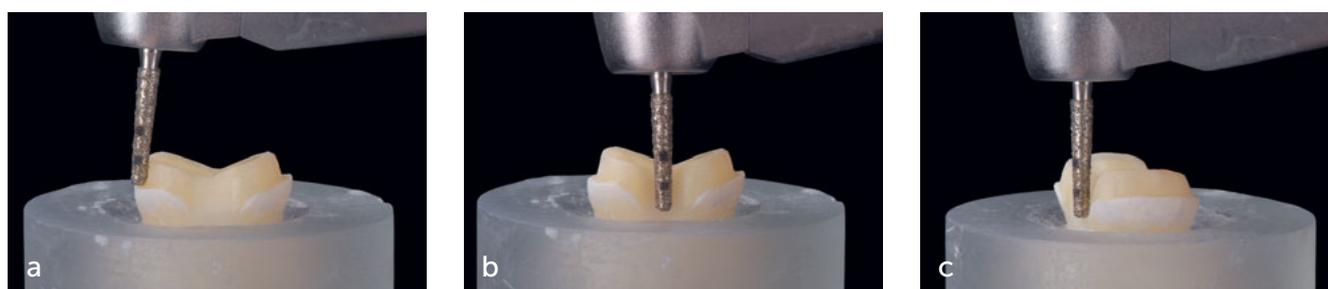


Fig 9a to c Shoulder preparation phase. The shoulder has a depth of about 1 mm.



Fig 10a to c Shoulder preparation phase: checking with a probe for 1 mm shoulder depth and rounding of internal corners.

when the shoulder was prepared, the enamel was eliminated in the most occlusal transitional part (Fig 8). To create the shoulder design around a 1-mm thickness, grooves were drawn along the perimeter buccally and palatally with a coarse-grit 151  $\mu$ m tapered bur (6847 KRD 314 016) at a further 2 mm toward the coronapical point. The grooves were then connected. In the interproximal areas, the margins were positioned

a further 3 mm apically, so there was a design with proximal slots more apically, with the finishing line with a minimum amount of enamel and close to the dentin. The shoulder depth was around 1 mm (Figs 9 and 10). The preparation was finished with a fine-grit 46  $\mu$ m bur (8847 KR 314 016; Komet), rounding the internal corners, and then final finishing with a bur of the same shape and diameter, being an extra-fine-grit 25  $\mu$ m

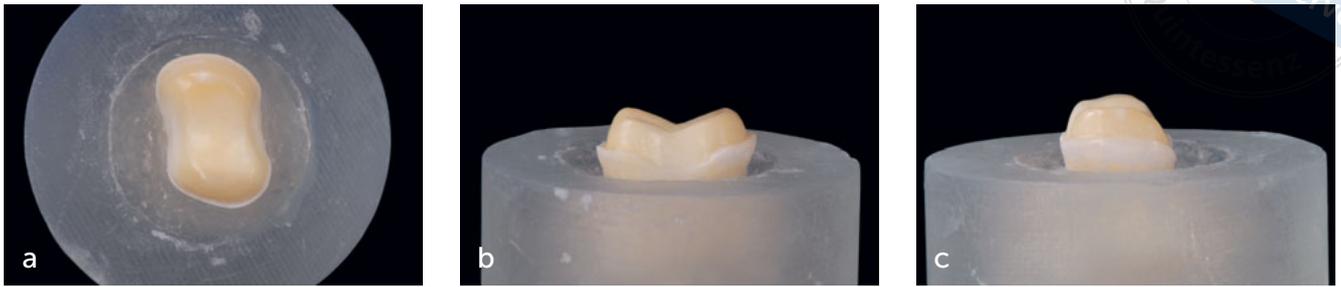


Fig 11a to c Shoulder preparation finalized.

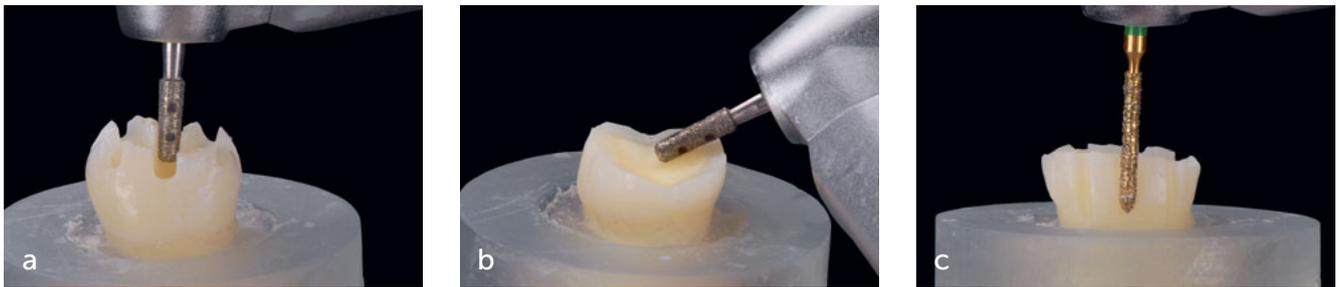


Fig 12a to c Full Crown modified chamfer preparation phase: occlusal reduction and vertical reduction grooves.

bur (959KREF 314 01; Komet). On the main surfaces, a rubber polisher was used for the final polishing (9608 314 030; Fig 11).

#### Group 4: Full Crown

In a clinical situation, this type of preparation is indicated when the crown tooth is severely damaged. In the present study, it was performed with a modified chamfer design with a perimeter thickness of about 0.6 mm. This preparation is more conservative compared with a regular crown using a classic porcelain fused to metal (PFM) restoration. The occlusal reduction was performed as for the other preparations, with 2 mm of occlusal reduction (even though the restoration was planned as monolithic lithium disilicate with an occlusal thickness of 1 mm). At this point, the cervical preparation margin was defined with the modified chamfer designs using a Domenico Massironi bur (2979

314 012; Komet) toward the tooth; the end preparation was maintained in the enamel at about 0.5 mm from the CEJ for the first reduction. For the final design, the finishing line was positioned at the level of the CEJ, so the preparation ended at the dentinal margin (Fig 12). The palatal and buccal vertical grooves were performed with the same bur, deepening by about half the width of the bur. Once the primary preparation was complete, the additional occlusal peripheral plan was drawn with a cant of around 45 degrees, rounding the internal edges (Fig 13). The secondary preparation was then prepared using finishing burs on the perimeter, and a finish line was performed with a fine-grit 46  $\mu\text{m}$  bur with a modified chamfer (8979 314 012; Komet). The finishing of the occlusal plane was performed using an extra-fine-grit 25  $\mu\text{m}$  tapered bur (959KREF 314 018), and the final polishing

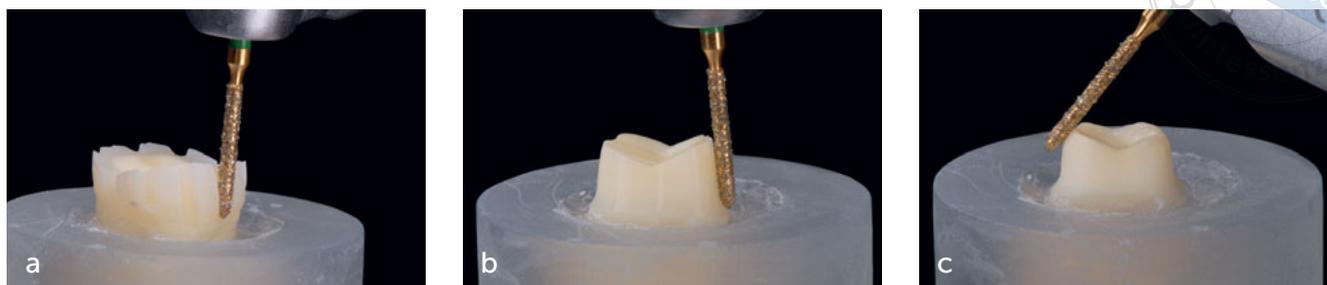


Fig 13a to c Full Crown modified chamfer preparation phase: main plan and occlusal peripheral plan.

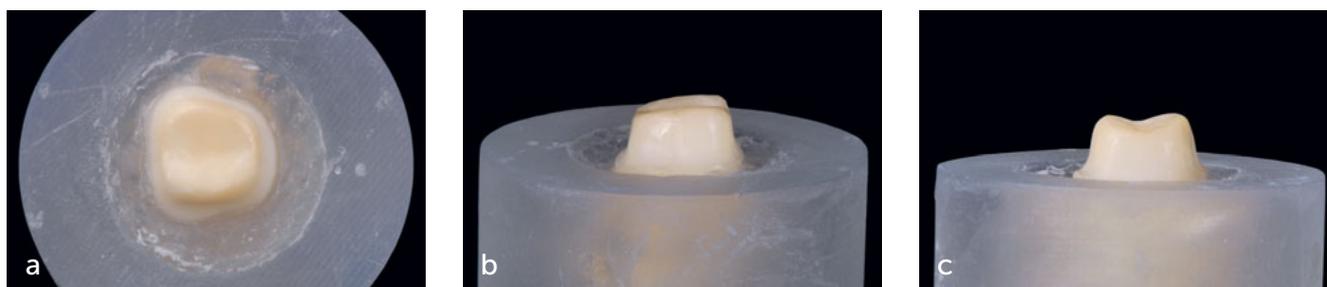


Fig 14a to c Full Crown modified chamfer finalized.

on the main surfaces was achieved with a rubber polisher (9608 314 030; Fig 14).

### Immediate dentin sealing (IDS)

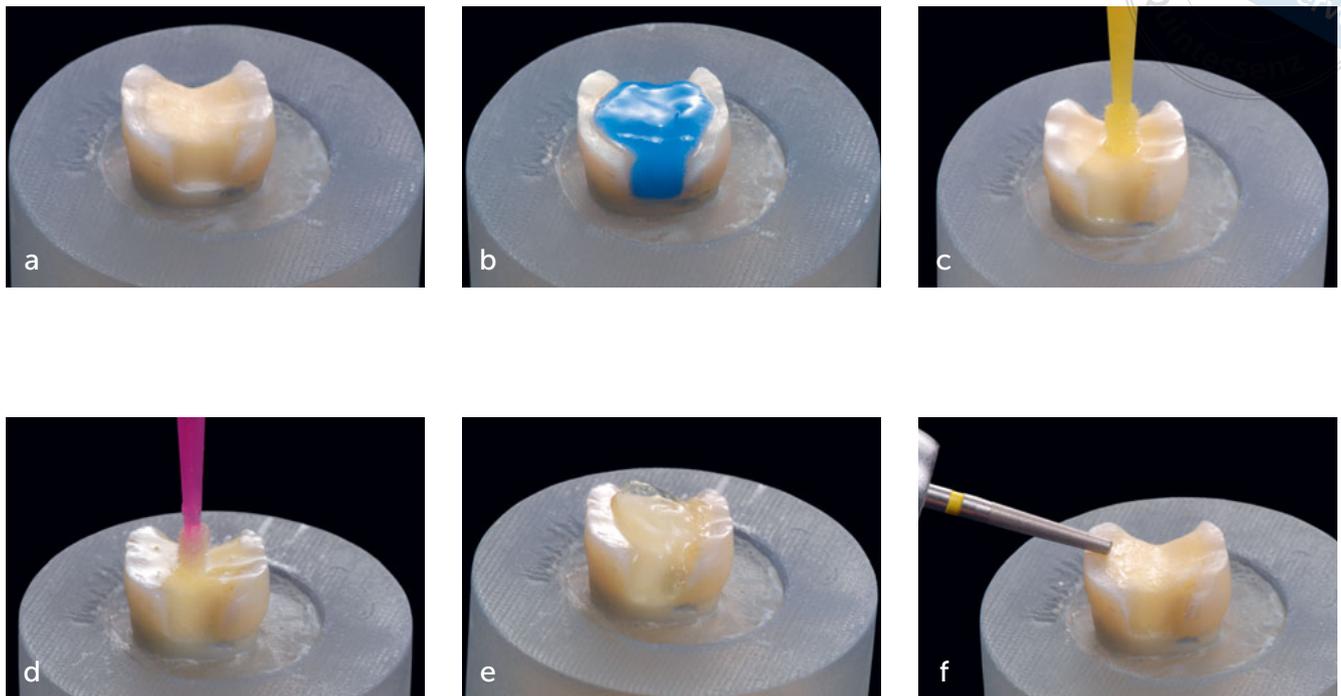
Considering the wide area of dentin exposed during the four preparation designs, in order to improve the quality of the final bond strength on dentin, IDS was performed on the exposed dentinal areas before the impression (in the present study, a digital scan was performed).<sup>25</sup> This procedure is absolutely recommended, especially when there is a widely exposed dentinal area.<sup>26</sup> According to the adhesion protocols, even more than IDS is advisable. After creating the dentin hybrid layer, a composite resin buildup is performed to obtain a very stable substrate. In the present study, it was decided to perform IDS only, considering that no other types of cavities were presented, as no carious lesions occurred, and so

no buildups were needed. In this case, to perform IDS without buildups also allowed for a better understanding of the behavior of the different preparation designs.

For IDS on the samples, etching was performed (Ultra-Etch; Ultradent) for 15 s only in dentin, then chlorhexidine (galenic digluconate solution) 2% was applied for 30 s. This was followed by the application of primer (OptiBond FL; Kerr) for 60 s, and then drying. Bonding (OptiBond FL) was used for 30 s, then a light blow of air and light curing (Elipar S10; 3M Oral Care) was done for 30 s. Transparent glycerin (DeOx; Ultradent) was applied, and finally polymerization was executed for 30 s (Fig 15).

### Design of restorations and manufacturing

The molars were restored using the inLab 16 CAD/CAM system (Dentsply Sirona).



**Figs 15a to f** Immediate dentin sealing (IDS) steps: phosphoric acid etching, primer, resin adhesive, air block, and finishing of enamel margins with an ultra-fine-grit diamond bur.

Standardized overlays and crowns (first maxillary molar) from the inLab software database were adapted to the scanned teeth using the design tools included in the software. The minimal occlusal thickness of the restorations was 1 mm, and the spacer was set at 80  $\mu$ m.

The CAD/CAM procedures (design and milling) were performed by Clinica Sammarco in Manduria, Italy. Before cementation, the necessary adaptations were performed on the restorations.

### **Adhesive cementation**

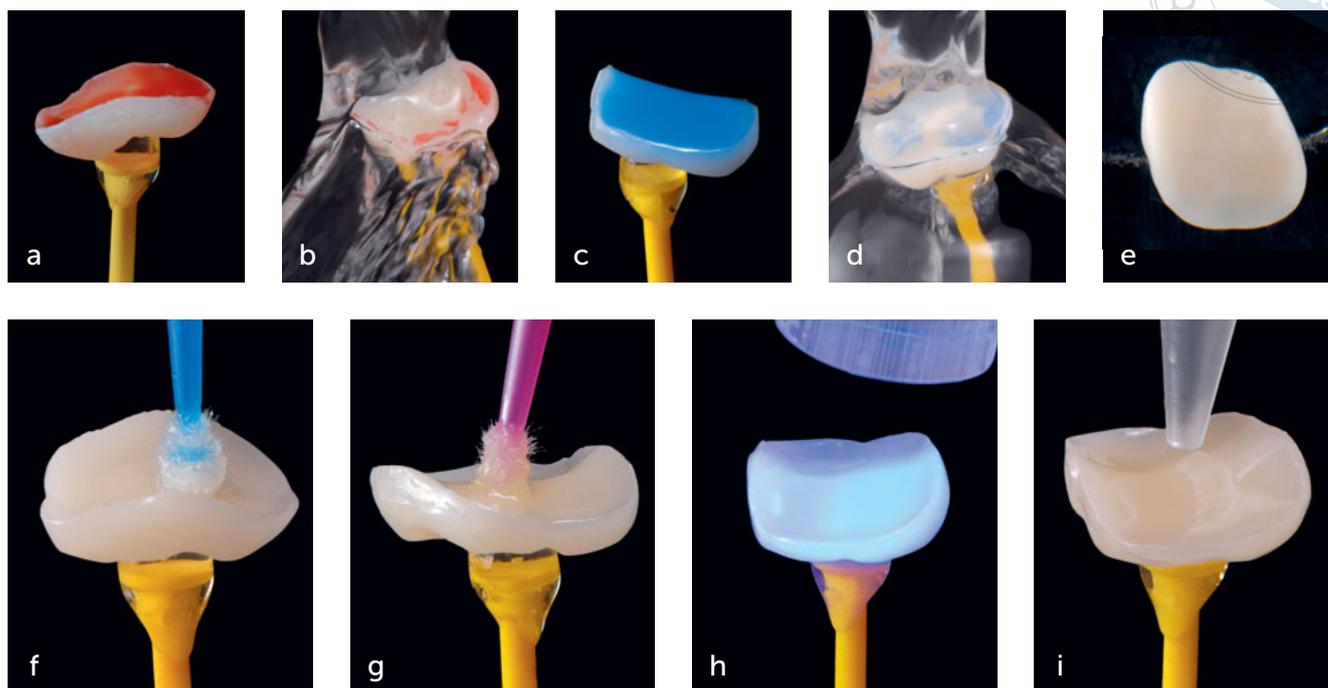
#### *Tooth conditioning*

The teeth were rehydrated in physiologic solution for at least 7 days. Airborne particle abrasion with a specific device (CoJet Prep; 3M Oral Care) was performed with 30  $\mu$ m aluminum oxide powder for 10 s (2.5 bar/30 to 42 psi, perpendicular, and at a distance of

10 to 15 mm), both on the tooth and on the bonding (of the previous IDS). Etching with 35% phosphoric acid (Ultra-Etch) was performed for less than 30 s only on the enamel and on the IDS bonding, then rinsing for 15 s, and drying. Application of primer (OptiBond FL) for 30 s and drying (considering that IDS was performed, it is possible that priming is not useful; however, it was performed in case of some undesired further exposed dentinal areas and to increase the wettability; it was also applied in cementation). A thin layer of bonding (OptiBond FL) was applied for 30 s, then a light blow of air and light curing (Elipar S10) was done for 30 s.

#### *Restoration conditioning and cementation*

Milled ceramic restorations were etched with 5% hydrofluoric acid (IPS Ceramic Etching Gel; Ivoclar Vivadent) for 20 s. After rinsing for 15 s, they were dried. The post-etching cleaning step was performed as follows:



**Figs 16a to i** PIAR lithium disilicate adhesive conditioning for cementation: hydrofluoric acid etching, post-etch cleaning (phosphoric acid etching, ultrasonic bath), silane coupling agent, resin adhesive, light curing phase, and dual-cure resin cement.



**Fig 17** PIAR samples after adhesive cementation and before testing.

The samples were etched using phosphoric acid 35% (Ultra-Etch) for 60 s, followed by rinsing for 20 s, and drying. Then, they were immersed in distilled water in an ultrasonic bath for 4 min. Silane (Monobond-S; Ivoclar Vivadent) was applied for 60 s, and then the samples were dried.

A thin layer of bonding (OptiBond FL) was applied for 30 s, then a light blow of air and light curing (Elipar S10) was done for 30 s. A dual-cure resin cement (RelyX Ultimate; 3M Oral Care), A1 shade, was positioned on the restoration, kept in position while the excesses were removed, then polymerized with a curing machine (Elipar S10) with three cycles for each side (occlusal, buccal, and palatal) for 30 s for each one. Rebonding (OptiBond FL) and polymerization for 30 s were performed. Block out with glycerin (DeOx) was applied, and then polymerization was done for 30 s. Finishing with a rubber polisher (9608 314 030) was then performed on the margins (Figs 16 and 17).



### Functional loading

Specimens were incubated in distilled water at 37°C for 24 h and were then cleaned for 10 min by sonication. A CS-4.4 chewing simulator (SD Mechatronik) was used for thermomechanical aging of the specimens. To simulate periodontal ligaments, a 2.5 mm-thick, even layer of Express 2 (3M Oral Care) was added to surround the specimens. A 6 mm-diameter steatite sphere was applied using an occlusal load of 50 N, a frequency of 1 Hz, and a downward speed of 16 mm/s. All specimens possessed a standardized anatomy and were similarly positioned for the sphere to be loaded onto the mesiobuccal, distobuccal, and palatal cusps (tripod contacts). The masticatory process was simulated through horizontal (0.3 mm) and vertical (6 mm) movements for a total of 1,200,000 cycles. During the test, the specimens were subjected to 39,000 thermal cycles between +5°C and +55°C by filling the chambers with water of the appropriate temperature for 30 s.<sup>27</sup> The TML was checked every 10,000 cycles by monitoring the mechanical action and water temperature within the chewing chambers. After TML, all specimens were examined for fractures under an optical microscope (Nikon E800; Nikon) at 50x stereo-magnification using an incident light. The data regarding the marginal integrity after this functional loading process will be provided in Part 2 of this article series (Ferraris F, Mascetti T, Tognini M, Testori M, Colledani A, Marchesi G. Comparison of posterior indirect adhesive restorations (PIAR) with different preparations designs according to an adhesthetics classification. Part 2: Effects on the quality margins. Int J Esthet Dent, in press).

### Fracture resistance test and failure analysis

The fracture resistance of the specimens was tested with a universal testing machine

(Galdabini Sun 500; Galdabini), which was set to exert an increasing force with a round 5 mm-wide stainless steel stylus onto the restored tooth at a speed of 1 mm/min. The tip of the stylus was positioned over the central fossa to achieve the tripodization of contacts along the cuspal inclines. The maximum load to fracture was registered and collected in a dedicated spreadsheet. Fractured surfaces were examined to evaluate failure modes, which were classified as follows: I) Extensive crack formation within the ceramic (enamel for sound tooth); II) Cohesive fracture within the ceramic or mixed failure (cohesive and adhesive) without dental involvement (on natural enamel for sound tooth); III) Fracture within the ceramic and tooth crown structure (the enamel and dentin of crown involved for sound tooth); IV) Longitudinal ceramic and tooth fracture involving the root.

All restorations were inspected under an optical microscope (Nikon E800). Scanning electron microscopy (SEM) operating in secondary electron detection mode was also used to analyze the surfaces of the failed samples. The cracked specimens were fixed to SEM holders, sputter coated with gold using a voltage of 35 mA for 120 s (Sputter Coater K550X, Emitech), and then examined with a scanning electron microscope (Quanta 250; FEI). The images were scanned at 25x, 50x, and 500x magnification with a high voltage of 30 kV, spot 5, and a working distance of 30 mm.

### Statistical analysis

Statistical software SPSS, version 14.0 (SPSS) was used for the fracture resistance analysis. Statistical differences between groups were analyzed using the one-way analysis of variance (ANOVA) and Tukey tests. The level of significance ( $P < 0.05$ ) was adjusted according to the Bonferroni adjustment.

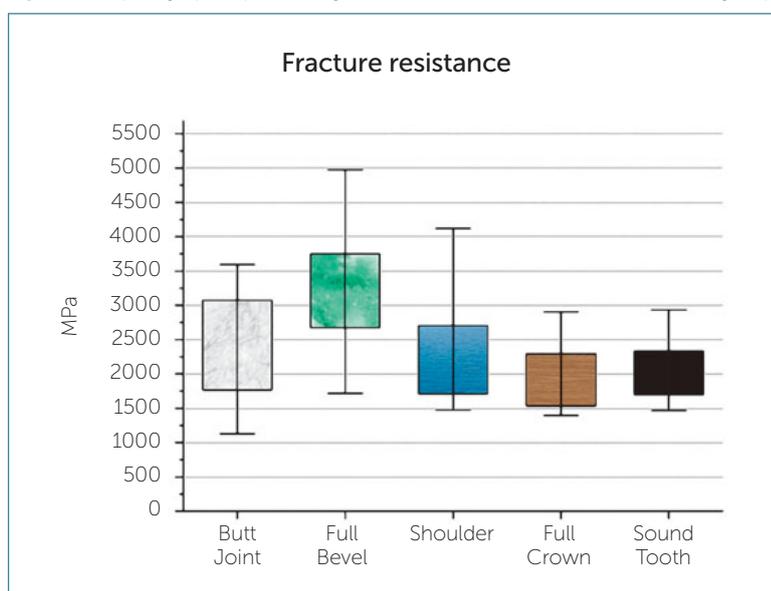


**Table 1** Mean fracture resistance (N) and standard deviation of groups

Groups	Mean (N)	Standard deviation	Minimum–maximum
1. Butt Joint	2462 <sup>B</sup>	813	3592–1180
2. Full Bevel	3216 <sup>A</sup>	879	4976–1715
3. Shoulder	2350 <sup>B</sup>	737	4120–1547
4. Full Crown	1940 <sup>B</sup>	455	2902–1395
5. Sound Tooth	2055 <sup>B</sup>	552	2935–672

\* Means with the same superscript letters indicate no significant difference between groups ( $P > 0.05$ ).

**Fig 18** Boxplot graph representing the mean fracture resistance (N) of the groups



Standard deviation: vertical lines; blocks represent the groups and show the minimum and maximum.

## Results

All specimens survived thermomechanical fatigue application. Neither cracks nor fracture failures were observed within the tooth structure or within the ceramic restorations, but some specimens showed small crack formations in the occlusal surface. The data regarding the marginal integrity after the functional loading process will be

provided in Part 2 of this article series (see above).

### Resistance to fracture

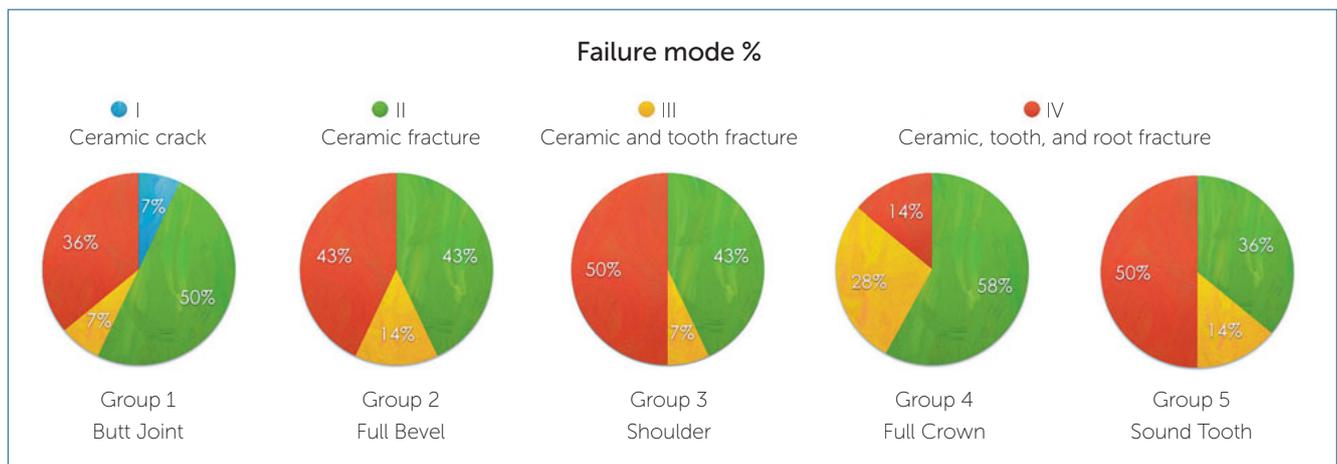
The mean values and standard deviations of the single load to failure test are listed in Table 1 and represented in Fig 18. The Full Bevel group showed statistically significantly different values compared with the other

Groups	Failure mode %			
	I	II	III	IV
1. Butt Joint	7	50	7	36
2. Full Bevel	0	43	14	43
3. Shoulder	0	43	7	50
4. Full Crown	0	58	28	14
5. Sound Tooth	0	36	14	50

**Table 2** Percentages of the four failure modes for each preparation design after single load to failure testing

I) Extensive crack formation within the ceramic (on natural enamel for sound tooth); II) Cohesive fracture within the ceramic or mixed failure (cohesive and adhesive) without dental involvement (the enamel and dentin of crown involved for sound tooth); III) Fracture within the ceramic and tooth crown structure; IV) Longitudinal ceramic and tooth fracture involving the root.

**Fig 19** Pie charts depicting percentages of the four failure modes for each preparation design after single load to failure testing



I) Extensive crack formation within the ceramic (on natural enamel for sound tooth); II) Cohesive fracture within the ceramic or mixed failure (cohesive and adhesive) without dental involvement (the enamel and dentin of crown involved for sound tooth); III) Fracture within the ceramic and tooth crown structure; IV) Longitudinal ceramic and tooth fracture involving the root.

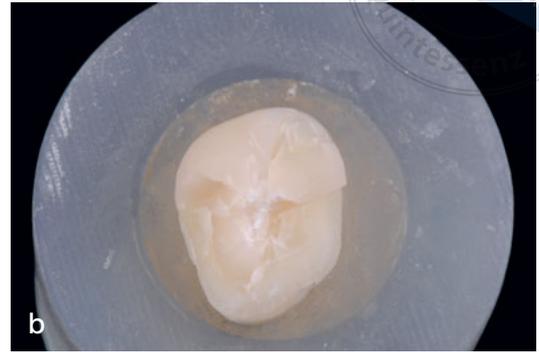
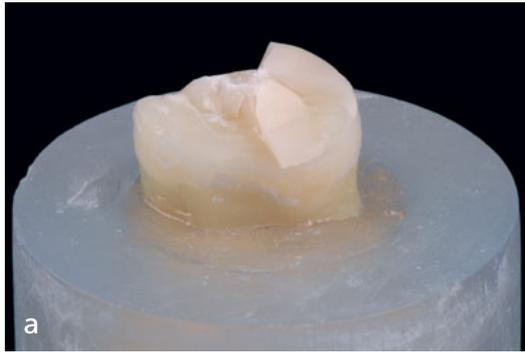
groups ( $P < 0.05$ ). The Butt Joint, Shoulder, Full Crown, and Sound Tooth groups showed no statistically significant differences. Failure mode analysis after the single load to failure testing is shown in Table 2 and represented in Fig 19. The Full Crown group failed predominantly because of extensive crack formation within the ceramic material or cohesive fracture limited to the ceramic (Figs 20 to 23). The Butt Joint, Full Bevel, Shoulder,

and Sound Tooth groups exhibited fracture failure that involved the ceramic material and the underlying tooth structure, irrespective of the preparation design. Longitudinal fractures that extended into the root were most commonly observed in the Shoulder and Sound Tooth groups (at 50% each).

Representative high-magnification SEM micrographs of the fracture mode patterns are shown in Figs 24 to 29.

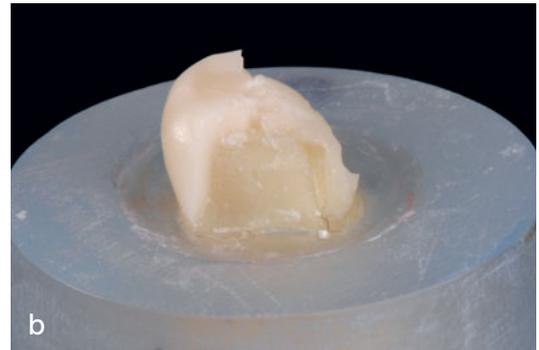
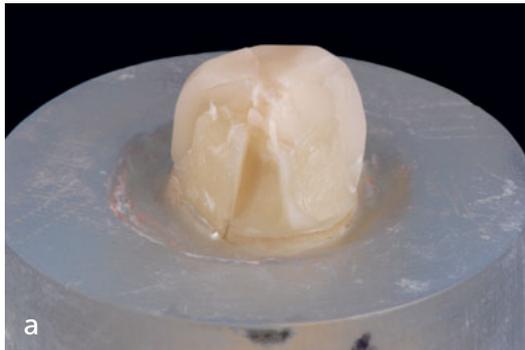
**Fig 20a and b**

Failure mode II fracture after single load to failure testing in a Full Bevel PIAR.



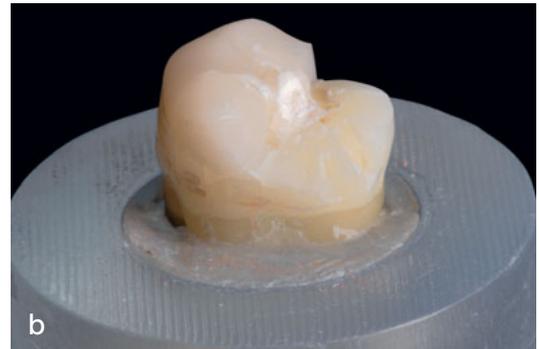
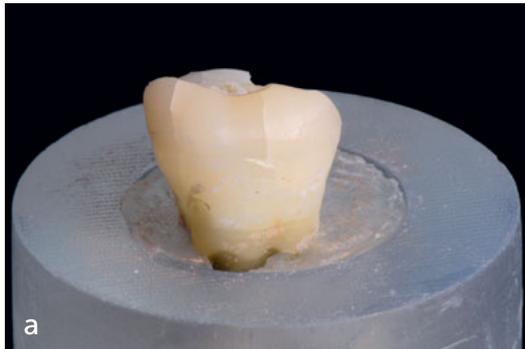
**Fig 21a and b**

Failure mode II fracture after single load to failure testing in a Full Crown PIAR.



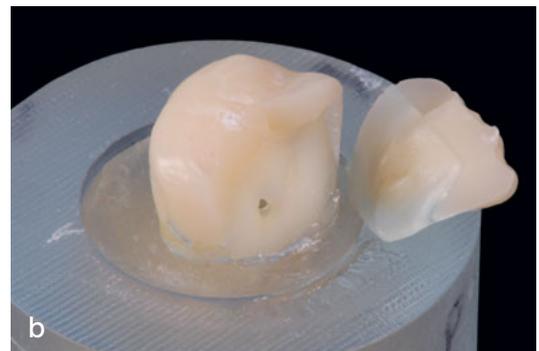
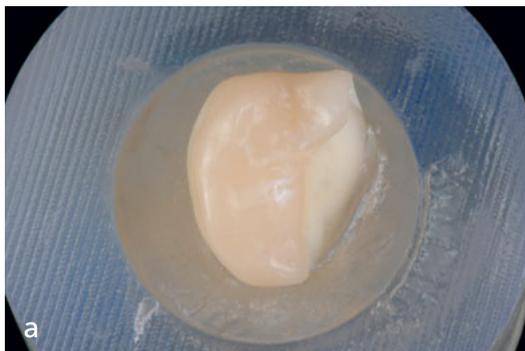
**Fig 22a and b**

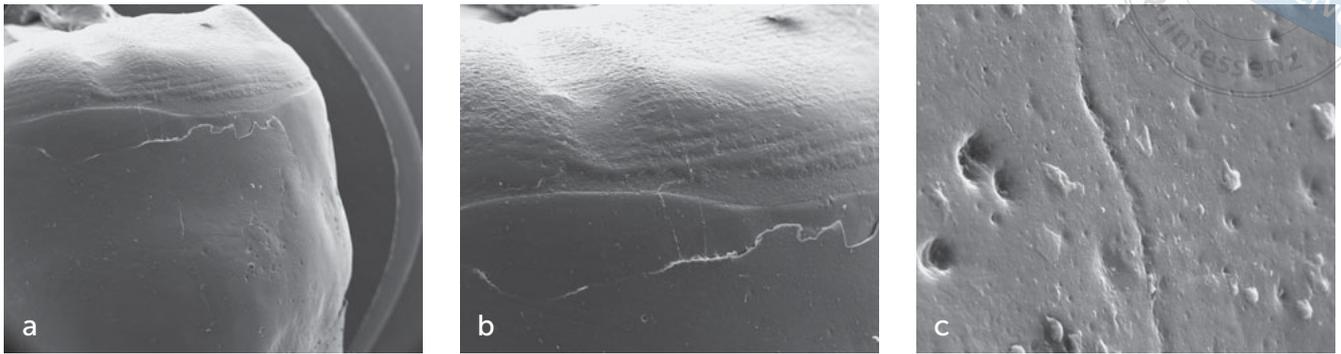
Failure mode III fracture after single load to failure testing in a Full Bevel PIAR (only a small part of the tooth preparation was involved).



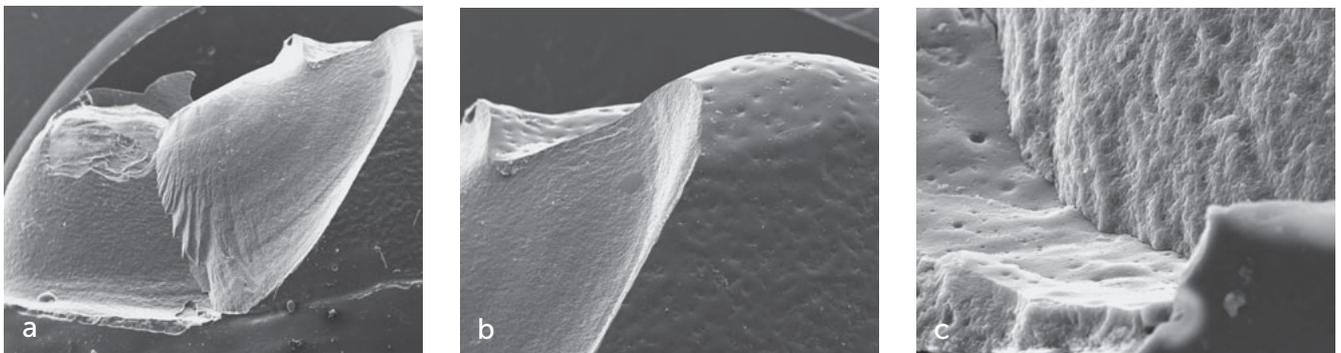
**Fig 23a and b**

Failure mode IV fracture after single load to failure testing in a Butt Joint PIAR.

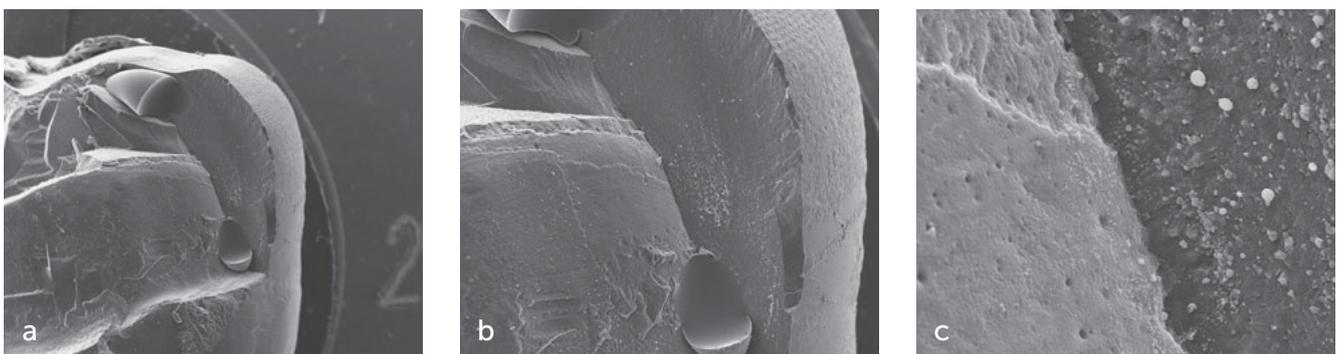




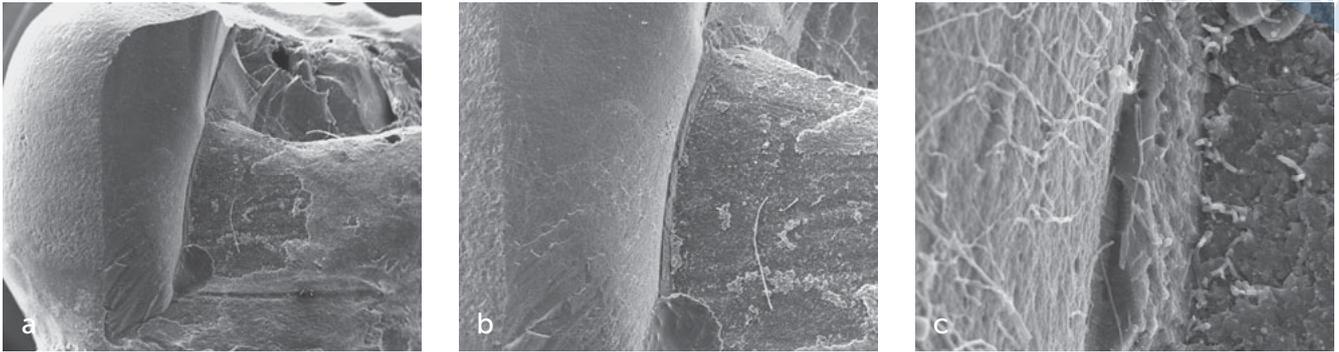
**Fig 24a to c** SEM analysis at 25x, 50x, and 500x magnification of a Butt Joint PIAR with failure mode I fracture after single load to failure testing.



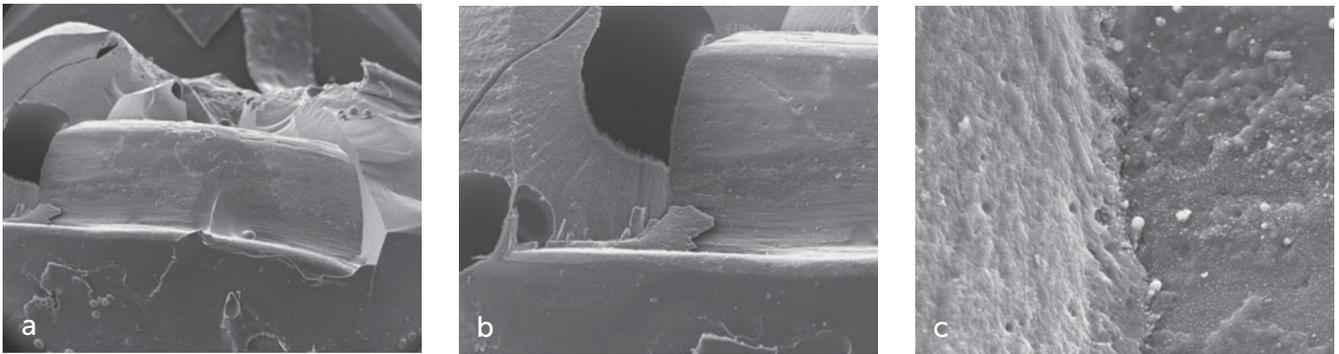
**Fig 25a to c** SEM analysis at 25x, 50x, and 500x magnification of a Full Crown PIAR with failure mode II fracture after single load to failure testing.



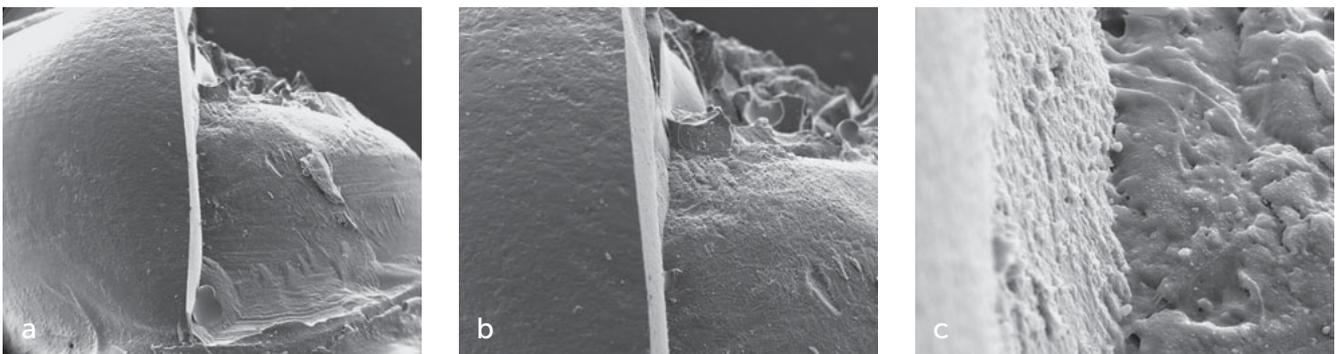
**Fig 26a to c** SEM analysis at 25x, 50x, and 500x magnification of a Shoulder PIAR with failure mode II fracture after single load to failure testing.



**Fig 27a to c** SEM analysis at 25x, 50x, and 500x magnification of a Full Crown PIAR with failure mode II fracture after single load to failure testing.



**Fig 28a to c** SEM analysis at 25x, 50x, and 500x magnification of a Shoulder PIAR with failure mode II fracture after single load to failure testing.



**Fig 29a to c** SEM analysis at 25x, 50x, and 500x magnification of a Full Crown PIAR with failure mode III fracture after single load to failure testing.



## Discussion

The null hypothesis that no significant difference would be found with respect to fatigue resistance among the PIAR groups, complete molar crown, and natural molar tooth was partially rejected. The Full Bevel group resulted in higher failure loads compared with the other groups. To obtain results comparable with the clinical situation with regard to the mechanical and morphological properties, freshly extracted human maxillary molars were used as test specimens. Minimal differences in the size of natural teeth did not show a difference with regard to the resulting fracture load values in *in vitro* tests.<sup>28</sup> Apart from the initial strength of a dental material, the microstructural fatigue resistance is of decisive importance for the long-term clinical success of a restoration. Thermal cycling reduces the fracture resistance of various dental materials, especially ceramics and polymers.<sup>29</sup> Ceramic restorations demonstrated a significant reduction of fracture values following fatigue. Lawn et al<sup>30</sup> associated the reduction of fracture resistance with an increased microcrack development in a wet environment under fatigue. To take this aspect into account, all the test specimens were artificially aged in a computer-controlled masticating simulator (1.2 million cycles).<sup>31</sup> The choice of parameters used in the present study was based on similar studies on mastication simulators.<sup>32</sup> The average human masticating cycles per minute is reported in the literature to be 58 to 120.<sup>33</sup> DeLong et al<sup>34</sup> and Krejci et al<sup>35</sup> described 250,000 masticating cycles as an average number for 1 year of clinical fatigue. To follow clinical recommendations and to create comparable data, a test time of almost 5 years was determined.

In the present experimental investigation, the location and morphology of the cavities, the preparation and finishing methods, and the cementation procedure corresponded

well with the PIAR protocol. The same restorative material (lithium disilicate), technique, cementation material, and dentin conditioning were used. The Sound Tooth group comprised a natural tooth without restoration and served as the control.

With the adhesthetics protocols, the first step is to perform a cavity analysis evaluating the resistance of the tooth after restoration. The structures to be evaluated are, in sequence: the interaxial dentin, ridges, roof of the pulp chamber, and cusps. The clinician has to consider cutting and covering the cusps to prevent possible coronal fractures, and needs to choose the right preparation design, especially regarding the thickness of the residual cusps.

According to the adhesthetics protocols, there are different indications for each PIAR preparation design.<sup>23,24</sup> The butt joint requires minimal preparation; the indication is a cusp reduction to protect the teeth and the cusp fracture in the case of an important cavity (both in vital and nonvital teeth) or when significant abrasion or erosion of the occlusal surface is evident and needs to be restored. Regarding the interproximal ridges, often in clinical reality the butt joint is associated with a slot (having a cervical shoulder with a depth of 1 mm), and this usually occurs for a MOD cavity (especially in nonvital teeth). The design of the bevel preparation is similar to that of the butt joint, but with the substantial difference of the presence of an inclined bevel, generally 45 degrees for an average length of 1 to 1.5 mm. This bevel is presented on the vestibular side but can also be on the lingual side or when more thickness and support are required for a restoration. The indications are the esthetic need for a more gradual integration of the restoration–root transition, and the existence of a larger surface of external enamel. The variation of full bevel involves a 360-degree bevel around the tooth, including the proximal ridges (that is more conservative



compared with the proximal slots) in a situation where there is an absence of extended and deep carious lesions. The shoulder is a preparation characterized precisely by a rounded shoulder that develops on the peripheral part of the design, and, generally, the central part is represented by the build-up made of a composite resin material. The indication for a shoulder preparation is a previous cusp fracture to the middle or cervical third; for this reason, it is not circumferential (covering all the cusps), but covers only those cusps already fractured. Another possible indication could be represented by an additional important structural protection with the cusp coverage in the case of a cervical gap, but this increased resistance to fracture is not confirmed by the data of the present study.

The main indication for a full-crown preparation is a severely damaged tooth (usually nonvital), but with at least the residual cervical ferrule effect. The 0.6-mm modified chamfer is a more conservative approach compared with the classical crown for PFM. In this type of preparation, all the peripheral undercuts must be removed, with a huge dentinal exposure; this is one of the aspects that makes this design more aggressive compared with the PIAR (in this study, the Butt Joint, Full Bevel, and Shoulder groups). However, in a classical way of thinking, this approach can guarantee a better mechanical strength. According to the data of the present study, the specimens in the Full Crown group with a 0.6-mm chamfer depth did not show a better fracture resistance compared with the other designs, which contradicts the idea of many clinicians who consider this design to be the safest with the highest strength.

After TML, all the ceramic restorations survived without fracture or chipping. Masticatory forces during normal function ranged from 50 to 250 N, and 500 to 800 N in the case of bruxism in the posterior

region.<sup>36</sup> Mean fracture loads for all restoration groups (~ 1940 to 3216 N) exceeded those values. The highest fracture resistance values (3216 mean) were achieved by the specimens in the Full Bevel group, which surpassed the fracture resistance values of the other groups. The lowest fracture resistance value was achieved for the natural tooth (672). This outcome could be explained by the fact that the full bevel design has a presence of more interaxial dentin; in fact, the other three preparation types were more extended in the proximal areas. Bevel on occlusal posterior veneers has been demonstrated as a conservative alternative for the treatment of severe abrasive/erosive lesions. A comparison of the results of the present study with those of other studies showed that occlusal veneers made of IPS e.max CAD were found to resist forces of up to 800 and 1000 N when their thickness was 0.6 to 1.00 mm or 1.2 to 1.8 mm, respectively.<sup>19,20</sup> A recent study by Sasse et al<sup>37</sup> obtained the best results with a 0.7 to 1.0 mm-thick restoration in terms of the survival rate after dynamic loading and fracture resistance, regardless of the bonding substrate (only enamel or enamel and dentin), whereas the performance of thinner restorations depended on the bonding surface, with the worst results obtained for 0.3 to 0.6 mm-thick restorations bonded only to enamel. In the present study, the restorations were mainly bonded to enamel margins, but a certain degree of dentin exposure on the occlusal surface was unavoidable in all the samples; nonetheless, the PIAR restorations were 1.0 mm-thick, and thus it was likely that the possible effect of bonding to dentin was decreased.

Most of the specimens in the Butt Joint and Full Crown groups showed mode II restorative failure after the fatigue test (see 'Fracture resistance test and failure analysis'). Due to the limited reduction during preparation, the underlying tooth structure was only

rarely involved in the fracture. From a clinical perspective, these ceramic restoration failures could be readily treated by renewing the restoration.<sup>3</sup> Fennis et al<sup>38</sup> demonstrated that thick overlay restorations showed higher static fracture strength but presented more drastic and irreversible failures compared with conservative ones. This highlights the advantage of minimally invasive strategies that preserve the structural integrity of the teeth. In the present study, only the Shoulder group showed catastrophic failure of half of the specimens; the Full Crown group showed a lower percentage of catastrophic failure than all the other groups.

There are some advantages to using a lithium disilicate overlay with a PIAR design. Compared with a full-crown preparation, covering the cusps of weakened teeth with a lithium disilicate overlay can improve the resistance to fracture and save tooth structure. Supragingival preparation margins are preferred for adhesive bonding and are recommended for caries prevention, and any marginal defects on supragingival restorations can be identified better at the controls than at the crowns.<sup>39</sup> Furthermore, with this type of preparation, it is easier and quicker to prepare the cavity, take the impression (using either an analog or digital method), place rubber dam, enable visual control of the marginal seal, and remove excess cement.

There are several limitations to the present study. The results are applicable only to the ceramic and luting system and preparation designs evaluated in molars. Moreover, the single load to failure method (see Table 1) resulted in a distributed load and did not replicate aspects of parafunctional occlusal habits that might involve individual cusp loading.

In conclusion, the results support the use of different preparations of PIAR using lithium disilicate ceramic. Further in vivo studies are needed to validate the

clinical performance of the more conservative preparation design.

## Clinical conclusions

Within the limitations of the present study, in terms of fracture resistance in a situation of overload in molar teeth (without endodontic treatments) restored with different PIAR designs using monolithic ceramic lithium disilicate, it is possible to present the following conclusions and clinical hypotheses:

1. Using unrestored and sound molar teeth as a reference in terms of fracture resistance, all the PIAR overlay designs (both partial and full-crown) performed equally or better.
2. The restorations in the Full Bevel group showed a significantly higher fracture strength than the natural tooth (Sound Tooth) and the other PIAR designs (both partial and full-crown).
3. The restorations in the Full Crown group did not show a better performance in terms of fracture resistance compared with the other partial PIAR overlay restoration types.
4. The preparation design in the Full Bevel group, which performed better in terms of fracture resistance, had the most conservative approach on the proximal ridges compared with the design types of the Butt Joint, Shoulder, and Full Crown groups. Although this aspect needs further investigation, it is possible to hypothesize that ridge preservation can add more strength to overlay-type restorations.
5. The fracture mode IV (longitudinal ceramic and tooth fracture involving the root) achieved a maximum of 2 to 3 mm of root below the CEJ. In the clinical situation, for all PIAR design types, it was possible to restore the tooth after the fracture, in some cases ideally with an additional procedure, eg, surgical crown lengthening or orthodontic extrusion.



6. The highest percentage of fractures limited to ceramic restorations (failure modes I and II) was shown by the specimens in the Full Crown (58%) and Butt Joint (57%) groups.
7. The specimens in the Full Crown group showed the most favorable percentages in terms of fracture types for possible new restorations, as only 14% involved both the crown and root (failure mode IV).
8. The highest percentage of fractures involving the root (mode IV) was shown by the specimens in the Shoulder and Sound Tooth groups (50% each).

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### Disclaimer

The authors declare that they have no financial interest in the companies whose products are included in this article.

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