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2022

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### How to cite

IGARASHI, Kensuke et al. Double-crown prosthesis retention using polyetherketoneketone (PEKK): an in vitro study. In: Journal of prosthodontics, 2022. doi: 10.1111/jopr.13512

This publication URL: <https://archive-ouverte.unige.ch/unige:166890>






Publication DOI: [10.1111/jopr.13512](https://doi.org/10.1111/jopr.13512)

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# Double-Crown Prosthesis Retention Using Polyetherketoneketone (PEKK): An In Vitro Study

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## Keywords

chromium alloys; double crowns; gold; ketones; PEKK; prosthesis retention; retentive force; telescopic crowns.

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Received: November 12, 2021

Accepted March 23, 2022

doi: 10.1111/jopr.13512

## Abstract

**Purpose:** To assess the retentive force of telescopic crowns using polyetherketoneketone (PEKK) high-performance polymer in relation to conventional materials over a long period of time in an in vitro setting.

**Materials and Methods:** Thirty-six sets of primary and secondary crowns were fabricated as per the double crown-retained prostheses approach. Six samples were included in each of the five test groups (1: zirconia/PEKK [Zr/PEKK]; 2: titanium/PEKK [Ti/PEKK]; 3: cobalt-chrome/PEKK [CoCr/PEKK]; 4: PEKK/PEKK; and 5: gold/PEKK [Au/PEKK]) and the single control group (gold/galvano-gold [Au/GA]). The insertion-removal test was performed for 20,000 cycles, and the surface condition was observed. Retentive forces were analyzed using two-way ANOVA ( $\alpha < 0.05$ ).

**Results:** The retention forces in groups Zr/PEKK and Ti/PEKK significantly decreased over time (group 1:  $p = 0.035$  and group 2:  $p = 0.001$ ), whereas retentive force increased significantly in groups PEKK/PEKK, Au/PEKK, and control (group 4:  $p = 0.001$ , group 5:  $p = 0.008$ , and control:  $p = 0.042$ ). Similar wear was observed on the primary crown in groups PEKK/PEKK, gold/PEKK, and control.

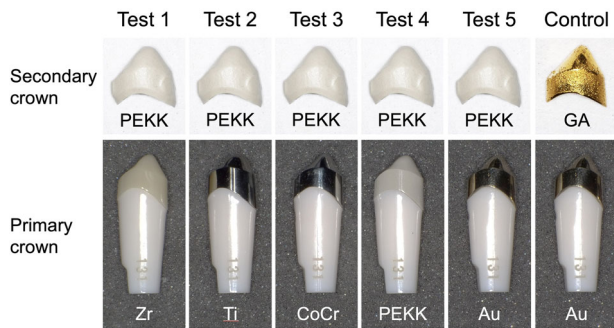
**Conclusions:** Groups PEKK/PEKK and Au/PEKK showed a transition of retentive force similar to the control group. Groups PEKK/PEKK and Au/PEKK had similar wear on the surface compared to control. Therefore, PEKK has a promising clinical potential.

Partially edentulous patients with a reduced number of remaining teeth or fully edentulous patients with strategically placed implants can have their original occlusion restored successfully with partial removable dental prostheses (RDPs) or overdentures (ODs), which can be retained using the double-crown system.<sup>1,2</sup> Double crowns are an effective retainer that can support and rigidly connect multiple abutment teeth or implants by transmitting occlusal forces along the vertical axes of the abutments.<sup>3–5</sup>

Implant overdentures (IODs) use a variety of attachment systems. Rigidly connected attachment systems include bar attachments, while the independent attachment systems comprise spherical/ball types, magnets, telescopic crowns, or stud-type attachments.<sup>6,7</sup> The success of ODs primarily de-

pends on the retentive capacity of its attachment element to sustain its long-term functionality.<sup>8</sup> Micro and macromovement between the retentive surfaces of an attachment system during mastication and removal of the OD may lead to wear and diminish retentive forces over time.<sup>9</sup> Normally, the combination of materials in OD attachments comprises a metal-metal, zirconia-metal, or metal-polymer contact.<sup>9,10</sup> Therefore, differences regarding surface wear and resistance to repetitive removal-insertion cycles might be found.

Telescopic attachment types are specific hybrid compositions of fixed abutments (i.e., primary inner crowns) and removable prostheses (i.e., secondary outer frameworks).<sup>11</sup> Depending on the retention mechanism, double crown-retained RDPs can be classified into three subgroups: parallel-walled telescopic



**Figure 1** All types of primary and secondary crowns. Abbreviations: Au, gold; CoCr, cobalt-chromium; GA, galvano-gold; PEKK, polyetherketoneketone; Ti, titanium; Zr, zirconia.

crowns, conical double crowns, and double crowns with additional retention modifications.<sup>12</sup> The fabrication of telescopic RDPs is highly demanding, and special skills are required for both the dental technician and clinician, which consequently increases the total cost of the double-crown prosthesis. Traditional materials used for the inner and outer crowns are gold-alloys and cobalt-chromium (CoCr) metal-alloys. With the introduction of computer-aided design and computer-aided manufacturing (CAD-CAM) technologies, inner and outer crowns, as well as the tertiary frameworks, are increasingly produced by precision milling.<sup>13</sup> Traditional materials like gold-alloys seem to be beyond the scope due to their high cost.

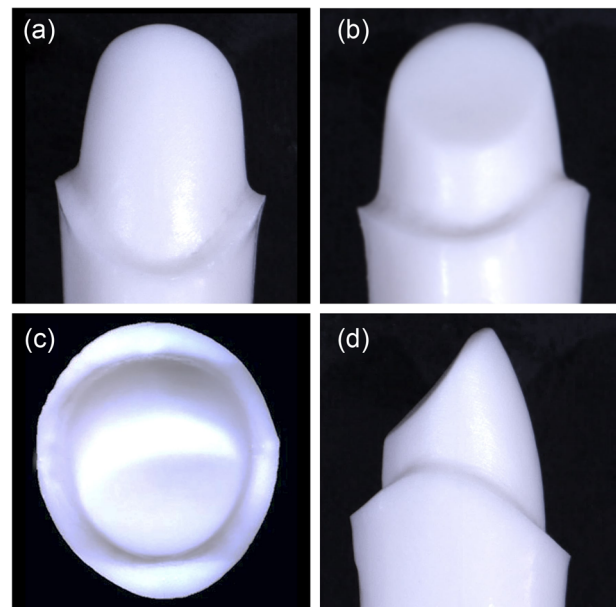
Recently, a high-performance polymer material has been introduced for provisional and definitive dental reconstructions.<sup>14,15</sup> Polyetherketoneketone (PEKK) is an amorphous or crystalline thermoplastic with high strength, rigidity, and resistance to hydrolysis that does not show any porosities or remaining monomers. Moreover, it is only the form and not the chemical property that is altered during the processing of PEKK.

Pektkon ivory (PEKK; C+M Cendres + Metaux, Biel, Switzerland) displays both amorphous and crystalline material characteristics.<sup>16</sup> In its crystalline form, it can be milled and used in digital workflows, which will help to reduce human labor and, thereby, cost. Consequently, PEKK can also be considered as material for RDPs or ODs.<sup>17</sup> However, scientific analysis of the best material combination for a primary telescopic crown and the corresponding secondary framework material is still unavailable.

The null hypothesis was that the retentive forces of primary crowns made of various materials, including PEKK and secondary crowns made of PEKK, would be equal to that of the gold standard, gold (primary crown)/galvano gold (secondary crown) after 20,000 connection and disconnection cycles. This *in vitro* investigation aimed to assess milled PEKK as an alternative material for double-crown prostheses.

## Materials and methods

Five test groups and one control group (Fig 1) were predetermined for examining the retentive force and long-term effects on single-unit primary/inner-secondary/outer combinations. Thirty-six artificial Typodont (A55AN-131, Nissin,

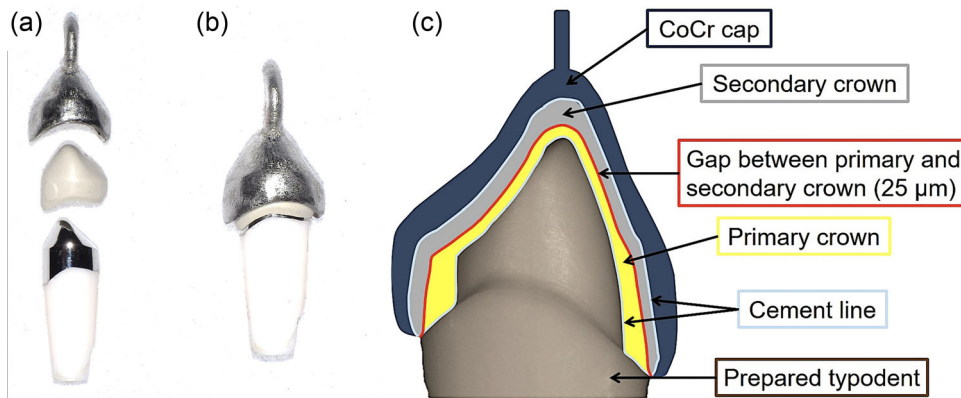


**Figure 2** Different views of an acrylic typodont right maxillary canine prepared as a double-crown abutment. (a) Buccal, (b) lingual, (c) incisal, and (d) mesial.

Tokyo, Japan) maxillary canines were prepared for a full crown design with deep chamfer of 1.0 mm width. The prepared teeth were designed with the following dimensions: 8.0 mm buccal height, 2.5 mm lingual height, 8.0 mm buccolingual width, and 7.0 mm mesiodistal width (Fig 2).

A total of 36 primary crowns were fabricated for the five test groups and one control group in this study: zirconia (Zr; group 1; DD Bio ZX,<sup>2</sup> Dental Direkt, Spenge, Germany), titanium (Ti; group 2; KZR-CAD Ti, Yamakin, Osaka, Japan), CoCr (group 3; KM-Cobalt Chrome, Kyocera, Kyoto, Japan), PEKK (group 4; Pektkon<sup>®</sup>, C+M Cendres + Metaux), and gold (Au; both group 5 and control, Cast Master Gold, IDS, Tokyo, Japan). Six crowns were fabricated in each group. The shape of the primary crowns was designed by the CAD-CAM system (D2000 scanner, 3shape, Denmark) to be the same design. From groups 1 to 4, primary crowns were milled from milling blanks, whereas wax patterns were milled and cast in the group using Au. Primary inner crowns were prepared to be 2 degrees for axial taper.<sup>3</sup> The friction heights of buccal and lingual were prepared to be 5.0 and 3.0 mm, respectively.<sup>4</sup> The thickness of the primary inner crowns was 0.6 mm. The secondary crowns for all test groups were made of PEKK. The PEKK samples were milled to have a 25  $\mu$ m space between primary and secondary crowns. The secondary crown for the control group used the galvano-gold (GA; AGC<sup>®</sup> Speed gold electrolyte 99.99%, C. Hafner GmbH, Wimsheim, Germany). GA samples for the control group were made by a dental technician, working at a private dental laboratory, who has experience with double crowns.

The primary crowns were cemented to the artificial typodont (Fig 2) using phosphate-modified resin cement (Panavia F2.0, Kuraray Noritake, Tokyo, Japan) according to the method of Fuhrmann *et al.*<sup>16</sup> The secondary crowns were cemented into



**Figure 3** Representation of a telescopic crown sample. (a) Prosthetic components before attaching a secondary crown to a cobalt-chromium (CoCr) cap. (b) Cobalt-chromium (CoCr) cap engaged on a secondary crown. (c) Cross-sectional schematic sample representation.

the CoCr cap (Fig 3) using the same resin cement as the primary crown. All the primary inner crowns cemented on the typodont, and secondary crowns cemented into the CoCr cap, were embedded into polyvinyl chloride models of uniform dimensions.

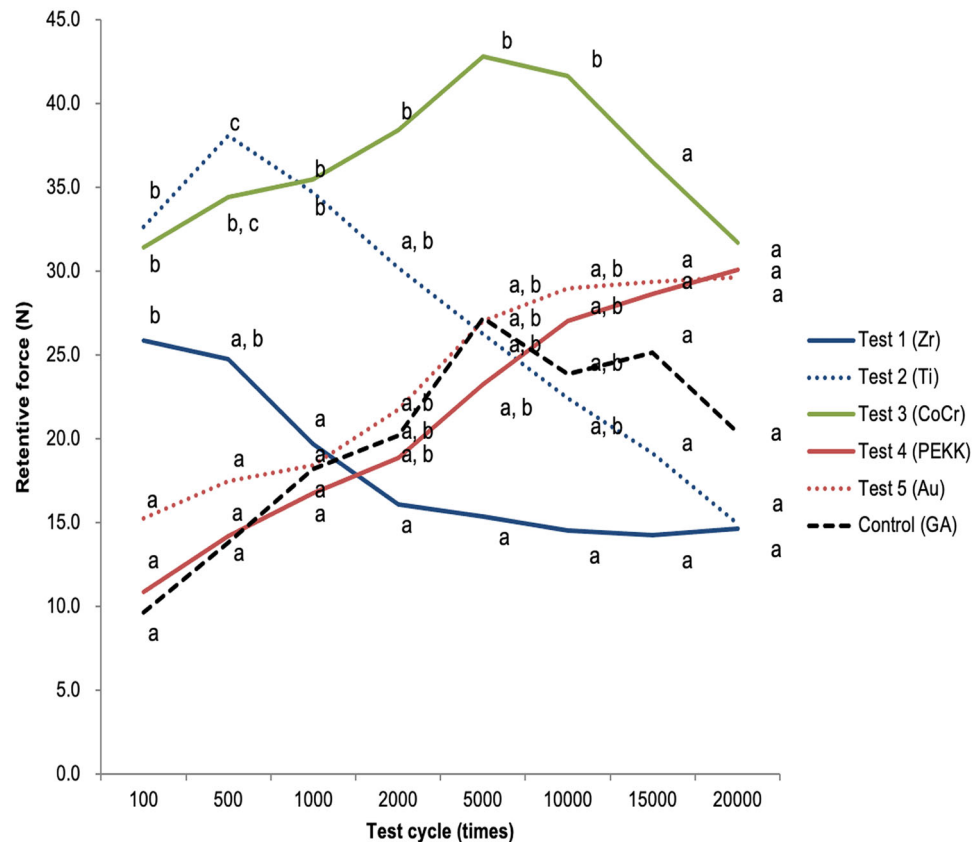
The tests were carried out with a linear-torsion all-electric dynamic test instrument (EMT-1KNV-30, Shimadzu Corp., Kyoto, Japan). The testing cycles were performed under wet conditions using artificial saliva (5 mL, Saliveht Aerosol, Teijin Pharma Ltd., Tokyo, Japan) in a custom-fabricated trough. The testing machine was programmed to seat the secondary crown on the primary crown with a force of 50 Ncm for 1 second<sup>18</sup> followed by a removal cycle with a frequency at 1 Hz.<sup>19</sup> The data for the first 100 cycles (referred to in this study as “baseline”) were omitted to stabilize the testing device, as the testing device provides multiple force readings per testing cycle. The retentive force (Ncm), which is used for further analysis, represents the absolute value of the force vector of the removal movement (absolute difference between initial and final force readings of the removal cycle). For analysis, the results are considered in cycles of 500, 1000, 2000, 5000, 10,000, 15,000, and 20,000. The number of cycles assigned experimentally simulates 13 years of intraoral function with a stipulated number of four insertion-removal cycles per day.<sup>19</sup>

Changes in the surface structure of the primary/inner crown were observed using an S-800 Hitachi stereoscopic electron microscope (SEM; Hitachi High-Technologies Co, Tokyo, Japan) to assess the condition of the surface of primary/inner crowns before and after testing. For statistical analysis, when the effect size (partial  $\eta^2$ ) of the interaction between insertion-removal cycles and test groups was 0.1, the required sample size was calculated as a study design that can detect statistical significance ( $\alpha = 0.05$ ,  $\beta = 0.8$ ). At this time, a total of 24 samples had the required sample size, and four samples in each group had the minimum required sample size. Power analysis was conducted for the effect size because specific estimates of the mean and standard deviation were not available from previous studies. Partial  $\eta^2 = 0.1$  was set as a medium effect size. Considering variance errors in the data, the sample size was set to 6 in each group. To compare the resistance transition with

the number of insertions and removals between the tested telescopic crowns, two-way repeated-measures ANOVA was performed with resistance as the dependent variable, the insertion and removal cycles as the intrasubject effect, and tested group combinations as the intersubject effect. This model includes an interaction term between the number of attachments and detachments and materials tested. Correction with Benjamini and Hochberg methods<sup>20</sup> was used for the pairwise comparison between the materials tested in the telescopic groups at each insertion-removal cycle and pairwise comparisons between the insertion-removal cycles in each group of double prostheses. A standard level of significance was set at  $\alpha < 0.05$ .

## Results

All the samples completed the 20,000 insertion-removal cycles. No fractures or decementations were observed during the testing. Retentive force was used as the dependent variable, and the number of test cycles (Time) was used as the test of within-subject effect. Two-way repeated measures ANOVA, including the interaction term, was performed with five test groups and one control group (Test) as the effect between subjects. Table S1 confirms that the Time\*Test interaction term is significant ( $p < 0.001$ ). Therefore, it was confirmed by Test that there is a difference between the test materials in the transition of the retentive force depending on the number of test cycles. The results of the retentive force in each cycle are shown in Figure 4. At the beginning of the insertion-removal test, significant differences were found between the groups; [Zr/PEKK vs. control:  $p < 0.0001$ ], [Ti/PEKK vs. control:  $p < 0.0001$ ], [CoCr/PEKK vs. control:  $p < 0.0001$ ], [Zr/PEKK vs. PEKK/PEKK;  $p < 0.0001$ ], [Zr/PEKK vs. group 5:  $p = 0.01$ ], [Ti/PEKK vs. PEKK/PEKK;  $p < 0.0001$ ], [Ti/PEKK vs. Au/PEKK;  $p < 0.0001$ ], [CoCr/PEKK vs. PEKK/PEKK;  $p < 0.0001$ ], and [CoCr/PEKK vs. Au/PEKK;  $p < 0.0001$ ]. At 2000, 5000, and 10,000 cycles, the only significant differences that appeared were between groups Zr/PEKK and CoCr/PEKK: [ $p = 0.002$  at the 2000 cycles], [ $p = 0.025$  at 5000 cycles], and [ $p = 0.006$  at 10,000 cycles]. In terms



**Figure 4** Graphical representation of retentive force of each cycle among groups. Small case letters indicate significant differences within groups. Abbreviations: Au, gold; CoCr, cobalt-chromium; GA, galvano-gold; PEKK, polyetherketoneketone; Ti, titanium; Zr, zirconia.

of retention differences, after 15,000 cycles, there were no significant differences among the groups.

The results of the differences in the retentive force compared to the baseline for each cycle are shown in Table 1. At the end of the tests, groups Zr/PEKK and Ti/PEKK significantly decreased in retentive force (Test 1:  $p = 0.035$  and Test 2:  $p = 0.01$ ), whereas groups PEKK/PEKK, Au/PEKK, and control significantly increased in retentive force (Test 4:  $p = 0.001$ , Test 5:  $p = 0.008$ , and Control:  $p = 0.042$ ). CoCr/PEKK increased in retentive force until it reached 5000 cycles. Then, it decreased in retentive force, so, overall, no significant differences were registered.

Figure 5 shows the primary crown surfaces before and after the insertion-removal tests. All the specimens incurred damage on the primary crown surface after the 20,000 cycles of insertion-removal tests. Although groups PEKK/PEKK, Au/PEKK, and control displayed similar damage on the surface, test group, Zr/PEKK showed the least amount of damage to the surface of the primary crowns.

## Discussion

The present study evaluated the retentive force of several material combinations between primary and secondary crowns for the double-crown system in a wet environment, simulat-

ing 13 years of use. It was intended to compare the retentive forces of double crowns using common materials, such as Zr, Ti, CoCr, Au, and GA, as well as including PEKK as a new material. Since prostheses using CAD-CAM technology are increasing in dentistry, several material combinations were compared against one another to determine the retentive force of double crowns and the wear of the surfaces of primary crowns at different insertion and removal cycles. Based on the present study, the null hypothesis of equal retentive forces compared to the control was rejected. Statistical differences in the retentive forces were found among the groups. Moreover, the tendency toward damage of the surface of the secondary crowns could be observed by SEM.

Before the implementation of CAD-CAM technology, primary and secondary crowns were cast by dental technicians using the lost wax technique.<sup>21</sup> Primary and secondary crowns were fabricated using Au, because of the stability and ease of processing, although casting crowns introduced errors. Therefore, a tooth loss of up to 32% at 10 years has been observed in double crowns.<sup>22</sup> A retrospective study of partial RDPs using double crowns reported a 10-year survival rate of 94.7%.<sup>23</sup> However, prosthetic tooth wear (6.3%) was the third most common reason for the failure of double-crown prostheses. Another article reported different classifications of the remaining tooth position and its influence on the survival rate of the

**Table 1** Intragroup retentive force differences after each insertion-removal cycle in all tested groups compared to baseline retentive force

	Variation (vs. baseline)						
	500	1000	2000	5000	10,000	15,000	20,000
<b>Test 1: Zr-PEKK</b>							
Mean	-1.08	-6.13	-9.75	-10.51	-11.30	-11.61	-11.20
95% CI lower	-4.85	-11.25	-16.66	-19.68	-18.88	-22.32	-21.52
95% CI upper	2.69	-1.00	-2.85	-1.35	-3.72	-0.90	-0.87
<i>p</i> -value	0.562	0.021	0.007	0.026	0.005	0.040	0.035
<b>Test 2: Ti-PEKK</b>							
Mean	5.42	2.02	-2.49	-6.43	-10.24	-13.56	-17.79
95% CI lower	1.66	-3.11	-9.40	-15.59	-17.82	-24.27	-28.12
95% CI upper	9.19	7.14	4.41	2.74	-2.67	-2.85	-7.47
<i>p</i> -value	0.006	0.500	0.467	0.227	0.010	0.026	0.001
<b>Test 3: CoCr-PEKK</b>							
Mean	3.02	4.07	7.04	11.40	10.24	5.13	0.28
95% CI lower	-0.75	-1.05	0.14	2.24	2.66	-5.58	-10.04
95% CI upper	6.79	9.20	13.95	20.57	17.82	15.84	10.61
<i>p</i> -value	0.196	0.161	0.107	0.058	0.068	0.391	0.956
<b>Test 4: PEKK-PEKK</b>							
Mean	3.34	5.91	8.02	12.40	16.16	17.77	19.21
95% CI lower	-0.43	0.78	1.11	3.24	8.58	7.07	8.89
95% CI upper	7.11	11.03	14.93	21.57	23.74	28.48	29.53
<i>p</i> -value	0.080	0.025	0.024	0.010	0.000	0.002	0.001
<b>Test 5: Au-PEKK</b>							
Mean	2.21	3.14	6.51	11.78	13.73	14.14	14.41
95% CI lower	-1.56	-1.98	-0.40	2.61	6.15	3.43	4.09
95% CI upper	5.97	8.27	13.41	20.94	21.31	24.84	24.73
<i>p</i> -value	0.241	0.257	0.089	0.024	0.001	0.011	0.008
<b>Control: Au-GA</b>							
Mean	4.20	8.58	10.58	17.57	14.25	15.55	10.72
95% CI lower	0.43	3.45	3.67	8.40	6.67	4.84	0.40
95% CI upper	7.97	13.70	17.48	26.73	21.83	26.25	21.04
<i>p</i> -value	0.030	0.002	0.004	0.000	0.001	0.006	0.042

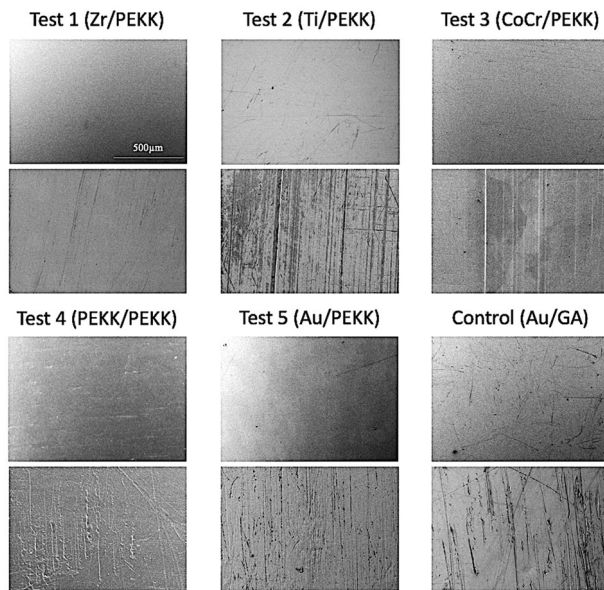
Abbreviations: 95% CI, 95% confidence interval; Au/GA, gold/galvano-gold; Au/PEKK, gold/PEKK; CoCr/PEKK, cobalt-chromium/PEKK; Mean, mean value of the differences with baseline; Ti/PEKK, titanium/PEKK; Zr/PEKK, zirconia/polyetherketoneketone. *p* value methods = Benjamini and Hochberg.

abutment teeth.<sup>24</sup> Also, the technical complication of loosening from friction was mentioned. The present in vitro study assessed single teeth. Therefore, an in vitro study using prostheses on multiple artificial teeth is needed in the future.

PEKK has a similar compressive strength to tooth dentine.<sup>16</sup> Therefore, PEKK has strong potential as an alternative material to metal. It was shown that PEKK/PEKK and Au/PEKK combinations in our study offered higher retentive force than that of the conventional control group (Fig 4). Comparing the retentive force transition among the tested groups, PEKK/PEKK and Au/PEKK combinations gradually increased from the initial test, and PEKK/PEKK showed the highest retentive force of all the groups tested by the final test. Thus, the lower cost, stability, and better retention force of PEKK may make it an excellent alternative to precious metals for double crowns. Moreover, PEKK shows a lower specific gravity than Au, and PEKK acts as a shock absorber.<sup>16,25</sup> Kotthaus et al conducted an in vitro study including PEKK for the double crown, and it showed acceptable outcomes.<sup>25</sup> However, that report did not

include Au/GA as the traditional combination in the assessment. The present study included an Au/GA group as a control group, and PEKK yielded more stable data than the Au/GA combination. Therefore, our study confirmed that PEKK could be an alternative material to metal components.

Ti/PEKK, CoCr/PEKK, and Zr/PEKK showed a higher retentive force in the initial test. The Ti/PEKK group increased and had the highest retentive force for up to 500 cycles. However, Ti/PEKK gradually decreased in retentive force until it ended up as the second lowest value. A titanium surface is stable because it oxidizes easily.<sup>26</sup> However, when titanium alloys run into friction with most metals or ceramics, the surface of titanium alloys produces severe adhesive wear.<sup>27,28</sup> The damaged surface of the titanium primary crown surface confirmed the issue with severe wear (Fig 5). Moreover, since all specimens were immersed in artificial saliva, the specimens were subjected to more strict and realistic conditions than a dry environment. Schimmel et al observed the retentive force of telescopic crowns using basically the same materials as the present



**Figure 5** Stereoscopic electron microscope images of primary crown surface before (above) and after (bottom) insertion-removal test (100x magnification). Abbreviations: Au/GA, gold/galvano-gold; Au/PEKK, gold/PEKK; CoCr/PEKK, cobalt-chromium/PEKK; Ti/PEKK, titanium/PEKK; Zr/PEKK, zirconia/polyetheretherketoneketone.

study.<sup>29</sup> That study used the Polyetheretherketone (PEEK) instead of PEKK and reported that the Ti (primary crown)/PEEK (secondary crown) combination showed the best results for retentive force. This may result from the lower compressive strength of PEEK compared to PEKK,<sup>16,30</sup> which may have resulted in less wear of the primary crown. Moreover, this study used Au as the primary and secondary crown for the control group. The present study used GA as the secondary crown for the control group. Therefore, the tendency when comparing materials with the control group seems a little different in the two studies. The retentive force of the CoCr/PEKK group decreased at 10,000 cycles. However, there were no significant differences between the baseline and the last retentive force test. Additionally, the CoCr/PEKK group had the best retentive force of all tested groups after 20,000 insertion-removal cycles. CoCr has high strength<sup>31</sup> and is relatively light; consequently, it is commonly used in dentistry, especially for RDP frameworks/substructures. However, CoCr may cause abrasion after some years in use (6.5 simulated years) as the retentive force decreased at 10,000 cycles. CoCr pieces from abrasion might induce allergies.<sup>32</sup> In the Zr/PEKK group, the retentive force continuously decreased test after test. Zirconia has the highest strength and hardness of all dental materials, but the least flexibility.<sup>33</sup> The hardness of zirconium may propitiate abrasion and lost retention force.

Some papers have investigated double crowns in *in vitro* studies using zirconia as the primary crown.<sup>34–36</sup> The retentive force between gold and zirconia primary crowns was compared using electroplated gold secondary crowns.<sup>34</sup> Zirconia primary crowns showed a stable low retentive force compared to the present study. However, gold primary crowns increased

the retentive force, same as in this study. Therefore, an Au/GA combination may increase the retentive force due to gold properties. An important difference is that Turp *et al*<sup>35</sup> set three different conus angles of the primary crowns, and the retentive force changed due to the taper angle. In the present study, the conus angle was set at 2 degrees, and it showed the lowest value of retentive force. Using zirconia as primary crown showed consideration of the taper of the angles. Another study used zirconia primary crowns coupled with zirconia and electroformed Au and PEEK secondary crowns.<sup>36</sup> This experiment showed the same tendency in both groups; however, the retentive force was lower than in the present study. The space between the primary and secondary crown might be influenced by the milling strategy or postprocessing protocol, as the present study showed a different tendency and a high retentive force. Therefore, the space between the primary and secondary crown needs to be considered.

Regarding the retentive force differences between the baseline and the end of the insertion-removal test, PEKK/PEKK and Au/PEKK groups displayed a significantly higher value compared to the other groups. Thus, it could be assumed that PEKK can be an alternative material for Au when conducting telescopic reconstructions. PEKK prostheses are fabricated with CAD-CAM technology, decreasing both the dental laboratory costs and casting errors. Hence, it might be better to use PEKK for the double-crown technique. Although the same space between primary and secondary crown was set for all groups at the baseline, the retentive force was significantly different among the groups. Indeed, this can be explained by the mechanical properties (*i.e.*, elastic modulus, Vickers hardness, and toughness) of the tested materials being different among the groups tested. Further investigation may be needed to determine the optimal space and design, combining several materials for the double crown-retained prosthesis.

Regarding the simulated intraoral stability of the tested materials, PEKK or Au can be an alternative material, equivalent to the Au/GA combination, for double-crown prostheses. The results may suggest that PEKK is a promising material for custom abutments used in tooth-borne fixed dental prostheses and IOD scenarios. However, in implant dentistry, PEKK has only been used as temporary abutments. Therefore, the use of PEKK as an implant-supported primary crown would rather be conceivable in a titanium base (Ti-base) concept, in which the primary crown is bonded extraorally to the Ti-base.<sup>37</sup> Additionally, despite individual studies having shown that sufficient adhesive bonding between PEKK and tooth surfaces is feasible,<sup>37,38</sup> a scientific consensus for PEKK bonding procedures is lacking. This lack of clarity entails a certain risk of complications when using PEKK as primary crowns. Another clinically critical issue is accuracy in the milling of PEKK, and the resulting marginal integrity.<sup>39,40</sup> The available data regarding the marginal integrity of copings<sup>41</sup> and frameworks<sup>39</sup> deemed PEKK within the clinically acceptable range (< 90  $\mu\text{m}$ ). Moreover, the retentive forces were different among the groups despite the same space between primary and secondary crowns. Additional *in vitro* studies may be required to discover the optimal space of various material combinations for double crown-retained prostheses.

## Conclusions

The PEKK/PEKK and Au/PEKK primary/secondary-crown combinations were superior in retention force performance compared with the Au/GA combination. The CoCr/PEKK group combination presented stable retention during the tests and the highest retentive force after a total of 20,000 insertion/removal cycles. Since PEKK/PEKK and Au/PEKK displayed similar surface wear to the control group, PEKK has a promising clinical potential.

## Acknowledgments

The authors thank Daishin Trading Co., Ltd and Wada Precision Dental Laboratories Co., Ltd. for their assistance in fabricating the samples. The authors wish to thank Satista Co., Ltd. for statistical advice. The authors declare no conflicts of interest. We sincerely thank Rabbi Shari J. Berman, Associate Professor at the Hirosaki University Graduate School of Medicine in Northern Japan, for professionally editing the English draft of this manuscript.

Open access funding provided by Universitat Bern.

## Funding

The authors declare that there was no funding for the study.

## Disclosure

The authors declare that they have no competing interests.

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## Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

**Table S1.** Test of within subjects' effects: two-way repeated-measures ANOVA